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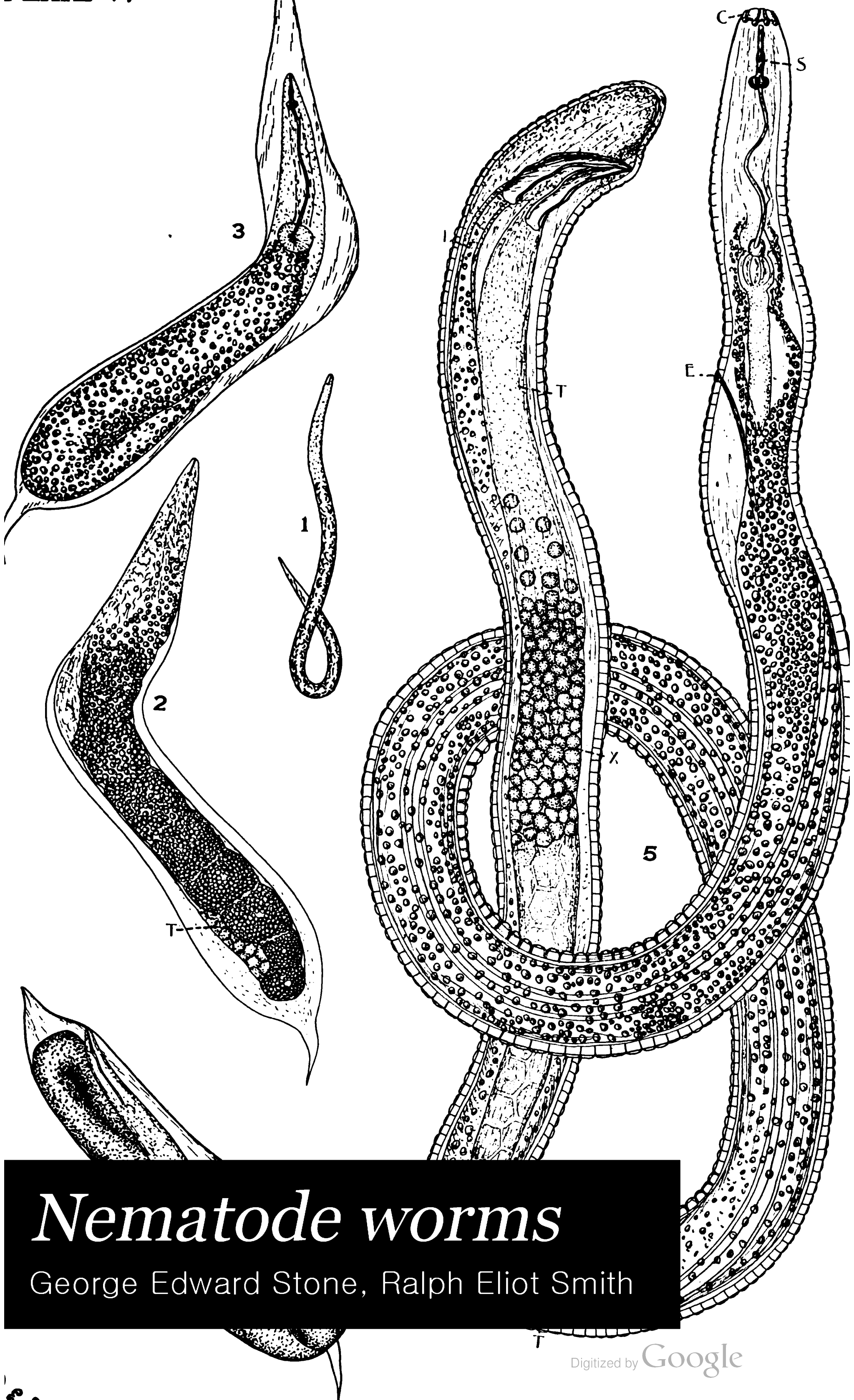

Nematode worms

George Edward Stone, Ralph Eliot Smith

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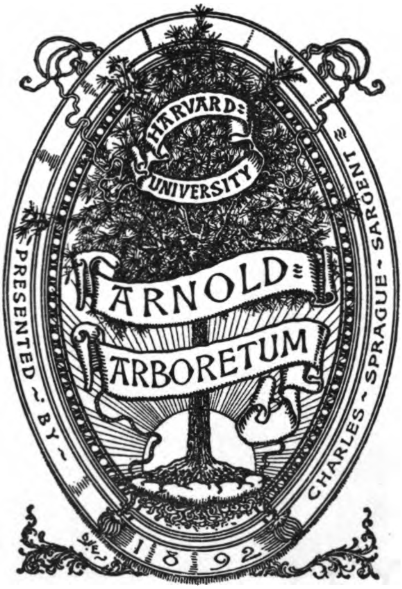

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HATCH EXPERIMENT STATION

OF THE

MASSACHUSETTS AGRICULTURAL COLLEGE.

BULLETIN NO. 55.

NEMATODE WORMS

NOVEMBER, 1898.

The Bulletins of this Station will be sent free to all newspapers in the State and to such individuals interested in farming as may request the same.

AMHERST, MASS.:
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1898.

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HATCH EXPERIMENT STATION

OF THE

Massachusetts Agricultural College,

AMHERST, MASS.

By act of the General Court, the Hatch Experiment Station and the State Experiment Station have been consolidated under the name of the Hatch Experiment Station of the Massachusetts Agricultural College. Several new divisions have been created and the scope of others has been enlarged. To the horticultural, has been added the duty of testing varieties of vegetables and seeds. The chemical has been divided, and a new division, "Foods and Feeding," has been established. The botanical, including plant physiology and disease, has been restored after temporary suspension.

The officers are :—

HENRY H. GOODELL, LL. D.,	*Director.*
WILLIAM P. BROOKS, PH. D.,	*Agriculturist.*
GEORGE E. STONE, PH. D.,	*Botanist.*
CHARLES A. GOESSMANN, PH. D., LL. D.,	*Chemist* (Fertilizers).
JOSEPH B. LINDSEY, PH. D.,	*Chemist* (Foods and Feeding).
CHARLES H. FERNALD, PH. D.,	*Entomologist.*
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HENRY M. THOMSON, B. SC.,	*Assistant Agriculturist.*
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ARTHUR C. MONAHAN,	*Observer.*

The co-operation and assistance of farmers, fruit-growers, horticulturists, and all interested, directly or indirectly, in agriculture, are earnestly requested. Communications may be addressed to the

HATCH EXPERIMENT STATION, Amherst, Mass.

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ERRATUM.

On page 35, line 20 and in foot note, for *Vahne* read Vanha.

DIVISION OF BOTANY.

GEORGE E. STONE AND RALPH E. SMITH.

In the presentation of this bulletin by the Botanical department we ought first of all perhaps to explain why we have undertaken a work which is zoölogical rather than botanical in its nature. For five or six years many complaints of damages caused to plants by nematode worms have been addressed to the Station. Since the trouble was not brought about by any vegetable organism such as a fungus it did not strictly belong to our consideration. The only other department of the Station to which it could be referred was the entomological, and since worms are not insects it might be questionable whether investigations of this nature would belong to that department. What is true in our Station seems to have been the case in most other states. We find more or less mention of damages caused by nematodes in the reports and bulletins of the different experiment stations, but in hardly any case has the subject been investigated. This is not due to negligence on the part of station workers, but simply to the fact that few stations have any department to which this work would fall, inasmuch as the study of worms belongs to specialists in the domain of zoölogy. As a consequence very little has been done in investigating the pest in this country and nothing at all in this section, though the necessity for such investigation has been continually increasing. It should be stated, however, that such study as has been made upon this subject has been done almost entirely by botanists.

Realizing the impossibility of making definite recommendations to those seeking advice in the matter and feeling that the subject was one of great importance to the gardeners of Massachusetts, we finally undertook investigations, the results of which are contained in this bulletin.*

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*We wish here to express our thanks to our colleague Prof. C. H. Fernald of the Entomological Division of the Station for many courtesies which he has shown us in this work.

There are many points of interest connected with the study of the early life history of nematodes which would delight the embryologists, but it was not our purpose to enter into this matter as it has no important economic bearing and does not fall within the sphere of station work. Our innumerable cultures of nematodes have furnished us with rare and abundant material for such investigation, but we have preferred to leave it to those especially practiced along the lines of modern zoölogical technique.

Our endeavor has been to acquaint ourselves with the main zoölogical features connected with the subject as far as possible and necessary, by careful examination of the most important literature relating to the subject as well as by actual research. In stating our results and drawing conclusions we have endeavored to present nothing which is not well established on fact and in principle. We have made no attempt to present a technical treatise upon the subject, but have aimed to give simply a clear and concise description of the nature of nematode worms and their relation to greenhouse plants, together with what we have been able to learn concerning means and methods for their suppression.

This investigation has been carried on in connection with the regular botanical work during portions of 1894, 1895, 1896 and 1897. That portion of the work relating to the life history and development of the nematode has been done by Mr. Smith while the investigations of the remedies to be used have been carried on by Mr. Stone. We have worked in co-operation with each other, however, and hold ourselves individually responsible for the entire work.

Nematode Worms in the Greenhouse.

The practice of growing plants under glass has seen many and important changes since its introduction. Beginning no doubt with the growing of a few plants in the window for the sake of their beauty in the winter, a comparatively short time has seen the introduction and development of the modern greenhouse, with all its accessories, improved methods, and appliances for growing plants, not to mention the great development in the nature and variety of the plants themselves. Especially recent is the practice of growing vegetables under glass, now carried on so extensively in the vicinity of all large towns and cities. During the last decade the value of greenhouse products in Massachusetts has more than doubled. In

1885 it amounted to $688,813; in 1895 $1,749,070; an increase of 153%.* But with this development in the methods and extent of greenhouse work there has been a corresponding increase in those elements and factors conspiring to make the success of such work difficult and uncertain.

All plants growing in the greenhouse in winter are, and must be, in an environment which is in a general way the more or less successful result of an attempt to imitate the natural conditions which exist in an ideal summer, and the degree of healthy and vigorous growth which the plants attain, and indeed their very existence, depends upon the success of this imitation. To be sure the gardener has an advantage over Nature in his absolute control over the heat and water supply, which are the two principal factors upon which the "ideal" conditions depend, but this advantage may or may not be profitable to him according as he employs it properly or improperly.

Of the factors upon which plant growth depends the most important are heat, light, air and water, (both in soil and air), as well as the mechanical and chemical nature of the soil. It might seem then that the proper handling of these factors should result in perfect success in plant growing, but such is not always the case. There are other factors which may come in and render of no avail the greatest skill and knowledge, which reaches only to this point. Artificial heating, ventilation, watering, fertilizing, etc., may be carried to perfection and still there are certain troubles or diseases which may attack the plants and hinder or entirely prevent their growth. The overcoming of such troubles is one of the most difficult problems of the gardener's art. They may be due to insects. These in the limited area of the greenhouse can usually be easily detected and destroyed. Another and more serious source of trouble lies in the attacks of fungous diseases, blights, mildews, rots, etc., which cause so much injury to plants growing in all situations. The Fungi causing these diseases are plants of low order and microscopic size, living as parasites upon other plants and causing more or less injury to them. They are much more likely to attack sickly or unhealthy plants than those growing vigorously. Their occurrence, therefore, especially in the greenhouse, depends to a considerable extent upon the health of the plants. Aside from insects and fungi, injuries may be caused to plants by other organisms of various kinds, among which the nematode worms are probably the most important.

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*Census of Mass. 1895, vol. VI., pt. 2, p. 327.

What Nematodes Are.

The Nematodes or Nematode Worms form a class of animals grouped under the Vermes or true worms. They are much lower in the scale than the larvae or caterpillars of insects, which are popularly known as worms and often cause injuries to plants, and are lower also than the earthworm, which is one of the most highly developed of the Vermes. The nematodes vary greatly in size, shape, and manner of life and include many peculiar and remarkable forms. Most of them however have at some period of their existence an elongated worm-like form, whence the popular names eel worm, thread worm, etc. Some keep this form during their whole existence and live in water, earth, decaying matter, and other damp places. Most of them are entirely harmless to plants and animals. They are usually of very small size, scarcely or not at all visible to the naked eye. Many different species of this kind exist abundantly in Nature. The well known "vinegar eel" is an example. A great number of nematodes however live for all or part of their lives as parasites; many on animals and a few on plants. Such forms pass through many most remarkable changes in their development. The Trichina of pork and many other animal and human-infesting worms are nematodes, while the tape worm, liver fluke, and in fact almost all organisms of that nature are closely related. The so-called hair-snake is a nematode, much larger than most kinds. In relation to plants, we have to consider, in this locality only a few, and, as far as we know, but one species of nematode. We know of no other among the many indigenous to our soil capable of causing any considerable injury to plants. All such trouble is due primarily to the one species, Heterodera radicola, (Greef.) Müll. There is a more or less prevalent idea that all kinds of nematodes cause injuries to plants, but such is certainly not the case. The soil may swarm with nematodes but, if our observations are correct, unless there are among them this one species no injury will result.

Symptoms Of Nematode Injuries.

The only definite indication of the attacks of Heterodera radicola is found in the roots of affected plants. These are more or less covered with what we shall call galls, that is swellings or enlargements of the roots, more or less roundish, but very irregular in shape and varying in size. These galls are sometimes very prominent both in size and number, but at other times are small, few, and inconspicuous. Their number depends entirely upon the abundance of the worms. The size and shape of the galls depends also to some extent upon the abundance of the worms and their location in the root, but in different kinds of plants we find galls which are somewhat characteristic in appearance. This is very natural when we consider that the gall is a growth of the plant itself and has no organic connection with the worm. As different plants produce different shaped leaves, flowers, fruits, etc., under the common influence of nature, so they may produce galls of different shapes though the worm which causes them is the same.

The smallest galls with which we have met occur on the violet, none being larger than a small pea and most of them being inconspicuous swellings near the tips of the rootlets. They might easily be overlooked in this plant, even if very numerous. In the cyclamen also the galls are small, but larger than in the violet. In the rose they seem to vary somewhat in different varieties, but are mostly of small size, especially on the smaller roots. On the main root they become larger and one correspondent writes that he has seen them as large as a duck's egg. This is an unusual size on any plant and must have been the result of a growth of considerable time. In the cucumber and tomato the galls are quite large and very prominent. Besides the formation of root galls the nematode attacks are indicated by the effect upon the vitality of the plant, though this effect is not particularly definite or characteristic. In very badly affected soil plants may be killed or very much stunted before reaching any considerable size. The tomato and cucumber seedlings shown in plate VII., figs. 3 and 4, were grown in such soil and never reached any considerable size. Only in extreme cases, however, is the soil as full of worms as this was, and more frequently the plants grow normally at first, but after reaching a considerable size begin to appear sickly. The leaves die at the edges, the plant stops growing and gradually fades away or sometimes collapses quite suddenly. The cucumber is perhaps the most liable to be killed outright, while roses, violets, etc., often linger for a considerable time, although this depends largely upon how badly the soil is infested. If the worms are abundant when the plants are first started their attacks will become evident at once. If only few at first they will have but little effect until several generations have developed, but this does not require a very long time. We feel very sure that more damage is caused to greenhouse plants by Heterodera radicola than is generally supposed. Working as it does in the roots of the plant and frequently producing even there very slight indications of its presence, plants might, and doubtless often do, linger along and finally die while the cause of the trouble is vainly sought above ground or in the soil, without its real location being suspected. If the roots were examined the casual observer might fail to notice anything unusual in some kinds of plants, even though they were badly affected. In all cases, therefore, where greenhouse plants become unhealthy and sickly and appear to be gradually dying without apparent cause, an examination for nematode galls on the roots should be made.

Galls Due to Other Causes Than Nematodes.

It must not be understood that all galls or swellings on the roots of plants are due to nematodes. There are other agencies and organisms producing a somewhat similar effect as regards superficial appearance, among which two are the most important. These are two low vegetable organisms, the one (Plasmodiophora Brassicae, Wor.) causing the well known "club root" of cabbage and turnip, and the other, a bacterial organism producing galls or "tubercles" on the roots of plants of the order Leguminosae. Plasmodiophora Brassicae is one of the very lowest plant organisms, consisting simply of a homogeneous mass of protoplasm or plant substance and having no distinct parts, organs, or tissues. It lives as a parasite in the roots of the cabbage, turnip, kohl rabi, radish, shepherd's purse, and other plants of the order Cruciferae, and produces an effect sometimes very similar to that of the nematode. We have seen roots of tomato affected by nematodes and those of cabbage with "club root," which could not be told apart except by the odor of the cabbage or by microscopic examination. The two things, however, are quite distinct, having nothing in common except their general appearance. The club root organism enters the root in the form of minute spores and then increases in bulk so as to cause a distension of the cells and consequent enlargement of the root into "clubs," Its effect can usually be distinguished in this locality from nematode injuries by the plants which it affects. Any galls on the roots of cruciferous plants growing out of doors in summer may usually be considered as club root.

The other gall-producing organism affects clover, pea, bean, lupine, horse bean, cow pea, vetch, and all other *legumes* or plants of the order Leguminosae. It is a bacterial or microbe-like organism consisting of extremely minute single cells, each cell being a complete individual in itself. These little organisms enter the roots of leguminous plants from the soil and reproduce and multiply there, causing the root by their presence to swell up into little galls or *tubercles* as they are commonly called. These tubercles are quite similar in appearance to nematode galls. Instead of injuring the plant, however, they have, on the contrary, a very beneficial and remarkable effect. It has long been known that leguminous plants have the power which is not possessed by other plants of obtaining free nitrogen from the air. This is of course very beneficial to them. What gives them this power was for a long time unknown, but it is now well established that this peculiar advantage is in some way connected with and due to the bacteria in the roots, though just how it comes about is not yet satisfactorily determined. We do not recall any leguminous plants cultivated to any extent in greenhouses, except perhaps one or two flowering plants, so that no great confusion with nematode injuries need arise from this source.

Root galls may sometimes be traced to insects or other causes, but not to any extent in greenhouse plants and therefore are not liable to be confused with nematode galls. Galls are sometimes formed on the root of the raspberrry by an insect (Rhodites radicum) which are quite similar. We know of no perennial outdoor plant in our climate which is affected by nematodes.

Nature of the Galls Produced By *Heterodera radicola*, And the Harmful Results Occurring From Them.

By breaking open a gall from the roots of any affected plant and carefully examining the fragments there may be seen with the naked eye or more easily with a hand lens, little, white, glistening, pearl-like bodies about the size of a pin head, imbedded here and there in the tissue. These are the mature female worms and the cause of the formation of the galls and consequent injury to the plant. Their number varies with the size of the gall, or, more logically, the size of the gall depends upon their number. In some parts of the root will be found minute pimple-like excrescences, usually of a yellowish color, just large enough to contain a single worm. From these the galls and number of worms contained varies indefinitely.

In order to get an idea of these abnormal root growths, let us first briefly consider the normal structure of the root in a plant like the cucumber. If such a root be cut across with a sharp knife there can readily be distinguished on the cut ends two different tissues or parts. The central part of the section is occupied by a more or less star or cross shaped portion differing in color and appearance from the other tissue which surrounds it. This is called the *central cylinder*, and the other part the *cortex*. Both are composed of variously formed *cells*, as are all parts of the plant. The cortex, (Pl. VI., fig. 2, c.) consists of comparatively large, thin walled cells which make it a sort of spongy tissue, the principal function of which is to absorb water from the soil. In this water are dissolved the substances forming the food of the plant. The central cylinder, (Pl. VI., fig. 2, p.) consists of several tissues, each having its particular structure and function. Its elements are mostly composed of cells of a firmer, thicker structure than those of the cortex and thus it serves to give the root its strength and stability, just as the woody portions do in the stem. Among the elements of this central cylinder one of the most important is a tissue composed of large, long, thick-walled, tube like cells, connecting end to end longitudinally to form passages from the root up through the entire plant to the leaves. (pl. VI., fig. 2, d.). Through these vessels, which are called *ducts*, the crude sap, i. e. water containing nutritive substances in solution, coming in through the cortex from the earth is carried up to the stem and thence to the leaves where it is transformed under the influence of sunlight into plant substance. We may, in a very general way, considering only the function of taking water from the soil, liken such a root to a bundle of tubes composed of some material through which water can pass, enclosed in a covering of spongy material; the tubes of course representing the ducts of the central cylinder and the spongy material the cortex. Imagining such a contrivance to be placed in water, it can readily be seen how the water might soak through the outer layer into the tubes and thence be carried wherever an impelling force might direct it. Such a force is supplied in the plant by the so-called *root pressure*, the force which circulates the sap.

If now a section be made of a fair sized nematode gall, a considerable difference in the arrangement of the tissues will be seen. The central cylinder no longer has its regular outline and central position, but forms an irregular, misshapen area, extending nearly to the outside of the root in some places, while in others it is far from the surface. The cortex also has an irregular shape and thickness, but it is much thicker than in the normal root. Here and there on the surface of the section will usually be seen the female worms or their remains, some near the edge and others at various depths in the root. Examination with the microscope shows a great disarrangement of all the root tissues. (Pl. VI., fig. 5). The cells of the cortex are increased in number and size, being affected especially in the vicinity of the worms, which are located mostly at the inner edge of the cortex at its junction with the central cylinder. In the latter portion of the root serious changes have taken place, as a result of which the injury to the plant is mostly to be ascribed. The ducts and smaller vessels, instead of running directly through the root as in the normal specimen are greatly distorted and deviated so that many of them run directly at right angles to their natural course, i. e. across the root, and a cross section shows their sides, which are marked with lines and dots on their wall, instead of their open ends as in the section of the normal root. Where one of the worms is located near or in the cylinder the vessels grow in such a way as to form an irregular mass completely enclosing it, and even where the nematode is in the midst of the cortex they are greatly deviated from their natural course. The size and shape of the galls, as we have already pointed out, depends largely upon the number and location of the worms, and also upon the kind of plant, but not, as far as we know, upon the worm itself. That is to say, we cannot conclude that galls of a certain shape indicate a particular kind of worm, for while each of the affected plants has a gall more or less peculiar to itself, the worm is the same in all. Large galls are formed where several worms attack the root at the same place. If they be close together and distributed on all sides of the root the resulting gall will be of quite regular shape. Irregular galls are formed where several worms locate on one side of the root, or at short distances from one another so that several small galls grow into one. Most of the galls start when the roots are very young, or on the younger portion, near the tips of older roots. Here the tissues are in a formative stage and the central cylinder is just beginning to form. Plate VI., fig. 1 shows a section of a young and normal root at this stage. The cortical tissue forms the larger part of the structure while the central cylinder consists of a limited area of small cells in which a few ducts are just beginning to develop. When a nematode attacks this young rootlet it very soon begins to appear like those shown on the seedlings in plate VII. Plate VI., figs. 3 and 4, show sections of these young galls. In fig. 3 are seen three young worms which are just entering the root (as shown from the exterior in plate VII., fig. 1). There were others no doubt on the opposite side which did not come into view in this section. Comparing this with the normal rootlet in fig. 1, we notice first of all the increased size, due principally to the increase in number and size of the cortex cells. The central cylinder no longer forms a definite mass in the center, but has separated into several portions and occupies an irregular area. The few ducts which have been formed are already distorted in direction and run obliquely. Fig. 4 shows a similarly affected root at a somewhat later stage. We see here a worm farther developed than those in fig. 3, the broad, large celled cortex, and the central cylinder divided into two parts in each of which appear several ducts and vessels growing in an oblique direction. From this stage the abnormal growth continues and the tissues become more and more confused and distorted until the gall reaches a considerable size and has the complicated structure shown in fig. 5.

The effect upon the vital function of the plant produced by this malformation of the root can be readily imagined. It is brought about principally in two ways; first, by the general interruption of all the functions, and second and particularly by the interruption of the normal flow of sap from the roots, caused by the distortion of the ducts. Continuing the comparison of the root with the bundle of tubes, imagine the latter to have become twisted, "kinked," doubled up, and tied into knots. It is very plain then that the passage of water through them would be hindered. The parts of the plant above ground, absolutely dependent upon the roots for moisture and food, must necessarily suffer from such an abnormal growth in a measure proportionate to its extent. A few galls on the roots produce no apparent effect. Where they are quite abundant the plant becomes stunted and sickly, and where the roots become completely covered with galls, as they do in badly infested soil, the plant is killed outright, for its food and water supply is entirely cut off. These effects, therefore, are not brought about directly by the nematodes, but only indirectly. That is to say they are not due to the direct action of the worm in feeding upon the root as is the case with the attacks of insects and fungous diseases, where the plant dies or sustains injury from the loss of its vital substance. To be sure the worms obtain their food from the roots after entering them and must cause some damage in that way, but far more serious must be the result of the derangement of the vital functions caused by the abnormal growth of the plant, which in trying to overcome the injury in the roots produces greater injury to its other parts. It is evident from published writings, even in experiment station bulletins, that a very general impression exists that nematode worm injuries are brought about by a swarm of little worms feeding upon the roots, much as insect larvae feed, but this idea is altogether wrong. The amount of food which the worms consume is insignificant and entirely disproportionate to the amount of damage caused. The structure of the affected roots, on the other hand, shows plainly that therein lies the chief source of injury.

Secondary Effects.

In this connection it will be proper to consider what we may call the secondary effects of these nematode attacks. This would include the attacks of other injurious organisms which are favored by the weakened condition of nematode affected plants. Among the most common of these organisms are those fungi which produce diseases. It is a well known fact that the least vigorous plant is most easily affected by disease. While it is true that some of the most destructive plant diseases attack the strong and weak alike, in the case of many others like certain "mildews", "blights", "spots", etc., the disease only appears on plants which for some reason are not growing vigorously. We believe that the destructive effects of the well known "violet disease" (Cercospora Violae) are greatly increased as secondary results of nematode galls on the roots. That is the galls have weakened the plants and thus given the fungus a foothold. In the same way we have seen the cucumber powdery mildew appear on nematode ridden plants while others in the same house which had no nematodes were likewise free from mildew. The tomato blight might easily be induced in the same way. We do not mean that nematodes are always the agent which induces these diseases,—poor drainage or ventilation, improper temperature or fertilizers, and a hundred other things may serve to weaken the plants and stop their growth, thus leaving them an easy prey to disease,—but we do believe that nematodes are at the bottom of much more trouble with plants than is generally suspected.

Another secondary result of nematode attacks is worth considering. In examining roots which are badly infested we find not only the worms of this particular species but also other kinds of nematodes, other low animal organisms, fungi, and bacteria, forms which have no power to attack the healthy root but which come in after the plant has been weakened and its root partly destroyed, and no doubt aid considerably in hastening its death. Thus the injuries caused to plants by Heterodera radicola are of three kinds; first the small direct injury by the worm feeding on the substance of the plant; second, and most important, the indirect injury brought about by the interference with the vital functions of the plant on account of the abnormal growth; and third, secondary effects as described above.

Description of Free-Living Nematodes.

A typical nematode of the free-living, harmless class is shown in plates I. and II. This is a form found in decaying roots which had been killed by Heterodera. It is a species of Rhabdites. The animal originates from an egg, (Pl. I., fig. 1.) which is of a noval shape, about .07 mm. ($\frac{1}{350}$ of an inch) in length and half as wide, and consists of a membranous covering inclosing a mass of granular protoplasm and fat globules. After being impregnated the contents of the egg divide into two parts (fig. 2) and then by continual division and development as shown in figs. 1-12, develop gradually into an elongated structure which assumes the form of a young worm, doubled up several times in the egg membrane. When fully developed it bursts the membrane and is discharged into the water or earth or wherever the mother may be. In this particular species the young are born alive. In others the eggs are discharged as soon as mature or when the young worm is partly developed, completing their development outside the mother. The newly hatched worm (fig. 13) is a minute elongated organism about .3 mm. ($\frac{1}{90}$ of an inch) in length, tapering to a rounded end at the head and a pointed tail behind. Its structure is quite simple. The body wall is composed of muscular layers and incloses an internal cavity almost entirely filled with the *alimentary canal*, which forms the very simple digestive system. This begins at the head end, in the mouth opening (fig. 15, m.) and runs back for about one-third the length of the body in a narrow tube, the *oesophagus*, which has a thick wall and two bulb like enlargements, one near the middle and the other at the posterior end, (fig. 15, x and b.). These parts are rather indistinct in the very young worm, but become more prominent as it grows older. From the oesophagus the alimentary canal broadens out into the *intestine* or *stomach* (s) which occupies most of the remaining length of the body, terminating in a narrow portion, the *rectum*, which has its outlet at the *anus*, near the posterior end. The whole body is filled more or less with granular protoplasm and fat globules. The only other organ distinguishable at this stage is the sexual, which originates in both sexes in a little cluster of minute cells situated close to the intestine, near or just posterior to the middle of the body. This is shown more enlarged in fig. 14. As the worm approaches maturity it increases in length and proportionally in width, the alimentary canal becoming more distinct and the sexual organs developing. The sexes now become distinguishable. In the female the sexual organ becomes an *ovary*. The cells composing it increase rapidly in number, extending toward both ends of the body. At the same time an opening called the *vulva* (v) is formed through the body wall on one side, about one third the body length from the tail. The worm has now reached the stage shown at plate I., fig. 17, or the somewhat later stage at plate II., fig 1. The ovary extends almost the entire length of the intestine, forming a long tube full of small, roundish cells, the immature eggs, and connected with the vulva or opening in the side of the body. Or we may regard it as two tubes, one extending forward and the other backward from the opening.

In the male, meantime, the sexual organ has also developed into a long tube, which however has no special outlet of its own but opens directly into the rectum just in front of its opening at the anus. This male organ is the *testis*, and in it the small round *spermatozoa* are developed. In the extremity of the intestine, just above the anus, there develops in the male a two branched, curved, sharp pointed *spicule*, which can be protruded from the anus and serves as an aid to copulation. For the same purpose there is also formed in the male a hood like expansion of the tail called the *bursa*. Plate

II., fig. 5, shows the mature male in its relative size to the mature female, fig. 4. Fig. 6 shows the posterior end more enlarged with the spicule (q), anus (y), bursa (z), and the testis (t). At this stage copulation takes place, the male and female being about equal in size, having a length of .8mm. ($\frac{1}{30}$ of an inch) the male being mature, but the female not yet fully developed. The male clasps the body of the female (Pl. I., fig. 18) by means of the bursa so that the opening of the testis is directly in contact with that of the ovary, and discharges its spermatoza into the small cavity which is situated just under the opening. The male has now completed its life and dies, while the female goes on to develop eggs and young. The body continues to increase in length and still more in diameter, assuming a somewhat distended, cigar shaped form (Pl. II., fig. 1). The eggs in the ovary begin to mature, those nearest the opening first, and soon the worm reaches the stage shown at fig. 2. The intestine is no longer the most prominent organ of the body cavity. That is now almost filled by the ovary, a long wide tube extending from the oesophagus to the posterior end of the body, filled with eggs in all stages of development. Soon the young begin to hatch and move about in the ovary, whence they are forcibly discharged through the side opening. In adult worms which were killed during examination the eggs continued to hatch but the young worms seemed unable to reach the exterior. They squirmed vigorously about, travelling from end to end of the body cavity (which finally became nothing but a sack, full of a living mass of young worms) and occasionally one would chance upon the vulva and protrude its head, but they always drew back again before getting out completely and showed by their actions that the forcible discharge by the parent which was observed in living specimens was necessary for their release. Fig. 3 shows a living mature female, and fig. 4 one which was dead and somewhat disorganized.

Plate IX., figs. 4 and 5 shows the male and female of another species in which the eggs are discharged when partially developed. Fig. 1 is a small male of another related species. In this is shown at (*e*) a small opening through the body wall just opposite the oesophagal bulb, which is the orifice of an excretory organ, a long tube running down the body which occurs in most nematodes but is not easily distinguishable. Fig. 2 shows the posterior end of this male more enlarged, bursa (z), spicule (q), intestine (o), and testis (t).

Besides the digestive, sexual, and excretory systems, nematodes also have a sort of nervous system, consisting principally of a so called *nerve ring*, which surrounds the oesophagus just behind its median bulb. This, however, is usually very indistinct and not highly developed. A circulatory system is entirely wanting in nematodes.

Description of the Parasitic, Gall Forming Nematode, *Heterodera radicola.*

(a) EARLY LIFE.

Turning now from this typical species of a nematode in its simplest form, to the gall forming species which causes the injury to plants, we shall find some similarities in structure and development and also some striking differences. The egg (Pl. IV., figs. 1-16), as in the other species is an elliptical or rather bean shaped body .1mm. ($\frac{1}{250}$ of an inch) in length, composed of a chitinous membrane inclosing a mass of granular protoplasm and fat globules.

The covering, although very thin, is extremely tough and very resistant to heat, cold, chemical substances, etc., affording to the egg contents a protection which is well nigh absolute against the ordinary influences of nature. In its earliest stage the mature egg consists inside the membrane of a loose, undivided mass with a nucleus in the centre. After fertilization the nucleus divides and two cells are formed (Fig. 3). These divide again and again passing through various embryological changes and developing into a young worm as shown at fig. 16. The worm moves about freely in the shell and finally ruptures it and escapes. In its earliest life it resembles the free living species having a similar form and structure. It is a minute worm-shaped creature about .33mm. ($\frac{1}{75}$ of an inch) in length, quite invisible to the naked eye. Plate VII., figs. 5 and 6, are intended to give an idea of the size of the worm at this stage. Fig. 5 shows it among the particles of a fine loam soil, while Fig. 6 shows an enlarged portion of an angle worm with two black lines upon it near the centre, the shorter of which represents a young nematode in its proportionate size to the angle worm. The longer black line represents the length of the mature male nematode, at the greatest length it attains at any time or in any form. Imagining the angle worm reduced to its normal size, some idea will be obtained of the minuteness of the nematode when similarly reduced. It is in this young stage and in the egg that the worm exists in the soil. Its structure is simple, consisting of a body wall containing the alimentary canal (oesophagus, intestine and rectum) and the almost indistinguishable rudiments of the sexual organ. In these respects it is very similar to the free living species. In its anterior end, however, within the mouth opening, is seen a structure not found in the ordinary forms. This is a small spear like organ, (Pl. V., s, fig. 5,) which can be moved about to a certain extent and assists the worm in penetrating roots. Most of the young worms when hatched are in the interior of the galls on the roots. They are able to escape without difficulty since the gall becomes decayed and disorganized and since their small size makes it an easy matter to force their way through the tissue, between the cells. Arriving in the soil they at once proceed to attack new roots if any be present, or if not they are able, as our experiments have shown, to exist for a considerable time without change, awaiting an opportunity for further development. Plate VII., fig. 1, shows young worms entering the tip of a rootlet. In this they no doubt make use of the spear like arrangement in forcing their way in. Having once effected an opening they are able to force their way between the loose cortex cells without difficulty. Having penetrated the root so that the whole body is covered, the worm comes to rest and its remarkable course of development proceeds. It does not simply increase in size retaining the same general form, as do the ordinary nematodes, but it begins to increase in diameter in the middle of the body, and in the course of about a week has a sort of spindle shape, broad in the middle and tapering towards both ends, (Pl. IV., figs. 3 and 4). From now on the swelling occurs more rapidly at the tail end, giving the body a club shape, (fig. 5). Thus far the sexes are indistinguishable but now appears a remarkable difference in their mode of development. The female continues to enlarge, but the male undergoes a remarkable transformation and returns to the slender, worm like form.

(b) DEVELOPMENT OF THE MALE.

Up to this point the development of the male, like that of the female, has consisted of an enlargement and broadening of the body. It now, however, ceases to enlarge in this way and begins to draw in from the body wall and increase in length inside the wall, which keeps its original shape, though it is now simply a sac enclosing the worm with which it has no connection. The transformation which the male now undergoes is somewhat similar to the pupal or " cocoon " stage in insects. During its increase in length the worm is obliged to double over inside the old wall, first once, then twice and even three times. It now appears as shown in plate V., fig. 4, which stage it reaches in about four weeks after entering the root. The old skin still retains its tapering form at the head and sharp pointed tail. Within it is coiled the mature male worm which soon proceeds to break forth and seek its mate. The mature male is shown in plate V., fig. 5. It is a slender worm-shaped creature, having a length of about 1.5 mm., ($\frac{1}{17}$ of an inch), and a breadth of about .045 mm., ($\frac{1}{600}$ of an inch). The body tapers towards the head, at which end it is about half as wide as in the middle. Towards the posterior end the diameter is nearly uniform. The body wall is marked by quite prominent transverse striae. On the head end is a cap-like thickening of the wall with six grooved depressions radiating from the mouth opening in the centre. Strubell considers this as a boring appliance to assist the worm in forcing its way through the soil and roots. The spear is quite large and prominent, the three-lobed base and the enlargement at the centre being plainly visible. The oesophagal bulbs are rather indistinct. The excretory duct is seen at its opening near the beginning of the intestine and can be traced down through the body for some distance. The intestine, testis, and spicule appear much as in the free living nematodes. We are able to find no ground for Atkinson's* statement that the rare case of a two-branched testis occurs in this species. We have found the organ to consist of the usual single tube connecting with the intestine near the spicule. This connection, however, and the general structure at this point is very indistinct, the most prominent objects being the two walls of the intestine, which, to judge from his figure of the male, are what he has regarded as the two tubes of the testis. No bursa is found in this species, nor is one necessary, since the females are fixed in the roots during copulation. The male comes to maturity at a time when the female is still immature, and since its existence ceases very soon after it reaches the adult stage it is not always easy to find specimens. Working with old, mature galls as material we were puzzled for some time at finding plenty of mature females, but no males. In following through the development of the worm, however, by examining galls from affected plants at frequent intervals during their formation, it becomes evident that at the time when the females are mature the males have ceased to exist, but that they may be found without difficulty if looked for at the proper time.

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*Nematode Root Galls. Rep't Alabama Agr'l Expt. Station, 1889.

C. DEVELOPMENT OF THE FEMALE.

The early stages of the female worm are similar to and indistinguishable from those of the male. It does not, however, return to the worm-like form after once entering the root and beginning to swell up, but continues in the same way until it comes to have the gourd-like shape shown in plate IV., fig. 6. This swelling affects the body wall and also the intestine, which enlarges correspondingly. The animal retains its pointed tail-like process up to the stage when the male can be distinguished, but soon after this disappears and the posterior end of the body assumes a roundish form. This change takes place by the "moulting" or casting of the skin, a process which takes place several times (four or five) during the development of the worm. This moulting is very similar to that of insect larvae, the skin lining the oesophagus being cast as well as that of the exterior of the body. Plate IV., fig. 4, shows the female at the time when the male is just becoming distinguishable (plate V., fig. 2,) and in plate IV., fig. 5, the female is represented about one week later, i. e. at the time when the male has completed its transformation and become mature. At this stage the intestine of the female has become very broad at the posterior end and contracts suddenly to a narrow portion or rectum leading to the anus. The ovary has been developing from the immature sexual organ and now consists of a two-branched tube, starting at the posterior end of the body, where the sexual opening is just appearing close by the anus. The simultaneous maturing of the male and development of the sexual opening of the female leave but little doubt that copulation now takes place, though we have not actually observed it as we did in the free living form. The return of the male to the worm-like form is evidently an adaptation to enable it to reach the female, which is entirely immovable after entering the root. It is not probable, however, that the male is obliged to travel a great distance in order to find its mate, as the worms show a sort of gregariousness in entering the root and usually several locate near one another. The European nematode which attacks the sugar beet does not form galls such as we meet with here, but the females locate so near the surface of the root that in their increase in size they rupture the epidermal tissues and their posterior portions project into the soil, whence, according to Strubell, they are fertilized by the males. In our form, however, while some of the females are located near enough the surface for this to be possible, most of them are completely imbedded in the tissue of the gall, through which the male must penetrate in order to reach them. After copulation the male perishes and the female continues to develop. It still increases somewhat in size and in about five or six weeks from the time it entered the root it reaches its mature form shown in plate IV., fig. 6. It is now about 1 mm. ($\frac{1}{25}$ of an inch) long and more than half as broad, being visible to the naked eye as a little white pearl-like speck or globule in the tissue of the gall. It still retains the spear and oesophagal bulb, but the intestine is disorganized and indistinguishable. The body cavity is filled with fat globules which render it semi-opaque. In the most transparent specimens the ovary can be somewhat distinguished, consisting of two long tubes coiled about in the body, filled with eggs in various stages of development and uniting at the sexual opening at the posterior end of the body. Plate IV., fig. 7, shows the ovary removed from the body by crushing it open. The extremities of the two tubes are filled with a transparent mass of small cells, the undifferentiated eggs. Below this the eggs become more and more mature, developing fat globules and a very prominent nucleus. Fertilization takes place in the ovary tube so that the eggs located toward the opening are partly developed. Life becomes extinct in the female at the time when the eggs mature and there remains simply a cavity in the gall filled with eggs, young worms, and the remains of the old one. The young worms gradually find their way out into the soil, seek new roots to attack, and a new generation begins.

Recapitulation of the Life History of Heterodera and the Formation of its Galls.

Let us now briefly review the course of development of this worm and the galls which it produces. Young worms coming into the soil from previously affected plants wander about until they find roots suitable for their attacks. Aided by a spear-like organ in the head they force their way into the younger portion of the root and imbed themselves in its tissue. This irritation of the tissues of the plant causes an abnormal development of the root, consisting in an increased production of cells and a derangement of the tissues from their natural arrangement. The worms increase in length and much more in diameter, assuming a spindle and then a club shape. The females continue this swelling process until they have the shape of a gourd and a size just visible to the eye. They are now mature, and having been fertilized by the male previous to their maturity they produce eggs which develop into the young worms of the next generation. The life period of the female is about six weeks. The male worms do not remain in the swollen form, but after about four weeks from entering the root they change again into a slender worm-like form which enables them to move about and seek the females, with which they copulate and then perish. While the worms are developing, the abnormal growth of the root continues and results in a gall-like swelling or enlargement and such a disarrangement of the tissues that the progress of the sap through the plant is hindered to an extent depending upon the numbei of galls on the roots. This injury, together with that caused by the worms drawing their food from the plant, checks its growth and often kills it outright or so weakens it that fungous diseases come in and hasten its destruction.

Historical Review.

It is difficult or impossible to say just when the injurious effects of nematode worms on plants were first recognized as such. It is probable, however, that the first record of such injuries is that of Hermann Schacht,[1] a German botanist, who, in 1859, in connection with studies on the sugar beet, discovered what he described as "little white specks of the size of a pin head," upon the roots, which he correctly determined to be nematodes. Three years later Schacht published again, giving a more complete description of the subject of his discovery. In 1871, Schmidt,[2] another German, made investigations upon the subject and gave to the worm discovered by Schacht the name Heterodera Schachtii. Schmidt's work was continued by several different investigators, and in 1888

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1. Zeitschrift f. Rübenzuckerindustrie 1859, '61, '62.
2. Ibid 1871, 1872.

Strubell[3] published an elaborate treatise upon this nematode, which had become a most serious obstacle to sugar beet growing in Germany. In 1872 Greef[4] described a gall-forming nematode from Germany, giving it the name Anguillula radicola, which Müller[5] redescribed in 1883 under the name Heterodera radicola. This was a form closely allied to Heterodera Schachtii and was never satisfactorily determined as distinct from it. In 1889 Dr. J. C. Neal[6] published under the auspices of the Division of Entomology of the United States Department of Agriculture, a bulletin upon a gall-forming nematode which was and had been for a long time the cause of much damage to plants in Florida. This worm he described under the name Anguillula arenaria. Later in the same year Atkinson, (loc. cit.) of the Alabama Experiment Station, published a bulletin upon what was evidently the same species described by Dr. Neal but referred it to Heterodera radicola of Müller. In 1890 N. A. Cobb,[7] consulting Entomologist to the Department of Agriculture, New South Wales, published the results of an investigation on a root gall nematode occurring in that country, which he called Tylenchus arenarius and considered identical with Neal's species. This includes the most important general accounts of gall-forming nematodes from an economic standpoint which have been published, although the European literature of the subject is very extensive. Such work, it will be seen, has been very meagre in this country and confined to the southern portions. In addition to these more elaborate publications short notes upon nematodes have appeared in the bulletins of several Experiment Stations, and in various agricultural, horticultural, and floricultural publications, mostly within the last ten years. Many of these have contained errors and none have given any comprehensive account of the matter.

It is impossible to say just when the effects of nematode attacks began to be noticeable in greenhouses. The earliest reference which we have been able to find is in an article in the *American Florist*, April 15, 1888, by J. N. May, in which the writer states that he observed what he calls "club root" in violets in 1876. This without much doubt was the work of nematode worms. The trouble seems to have been common since about 1888, most articles on the subject having appeared since that time. It is now common everywhere and known to every gardener and florist.

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[3] Untersuchungen über d. Bau und d. Entwickelung d. Rübennematoden Heterodera Schachtii, Schmidt. Bibliotheca zoologica II., 1888.

[4] Sitzungsber. d. Gesellsch. zur Beförder'g. d. Naturwiss. zu Marburg 5 Dez., 1872.

[5] Neue Helminthocecidien und deren Erzeuger, Berlin, 1883.

[6] The Root-Knot Disease in Florida. Bull 20 U.S. Dept. of Agr., Div. of Entomology, 1889.

[7] Tylenchus and Root-Gall. Agr'l Gazette, N. S. Wales, Vol. I., p. 155. 1890.

Identity of our Species.

We have carefully examined the work of Strubell, Neal, Atkinson, and Cobb, and compared them with our own. Atkinson's excellent account of the Alabama species leaves no doubt that it is identical with ours. The only discrepancy of importance is in regard to the structure of the male reproductive organ, to which we have already referred in discussing the structure of the male. In all other respects his description applies perfectly to what we have found. That portion of Neal's work which relates to the structure and development of the worm is by no means complete and contains not a few obvious errors, but indicates nevertheless, without much doubt, that his species was identical with Atkinson's and that which we have investigated. Cobb, also, appears to have had the same species to deal with in Australia. It may therefore be assumed that the forms studied by Neal, Atkinson, Cobb, and ourselves, are all to be referred to the species which has been called Heterodera radicola, (Greef) Müll.

An examination of Strubell's very complete and accurate description of Heterodera Schachtii shows that our species, if not identical with that, is hardly more than a variety of it. The identity or distinctness of these species has always been unsettled. The only really distinctive character between the two of which we have been able to find any statement is that of Atkinson in regard to the male testis, and of which, as already stated, we doubt the validity. Aside from this we find nothing which could not be considered as individual variation or at most a difference of variety. We were able to examine a few mature females of H. Schachtii brought by Dr. Stone from the Experiment Station at Halle, and found them apparently identical in structure with our H. radicola, but we were not able to compare the two in all stages of development. It would seem remarkable that forms should exist agreeing so completely in general structure and in the details of so unique a course of development and yet be distinct species. Certain violet roots sent in for examination by a gardener in this state were found to be infested with a nematode agreeing in every way with the ordinary H. radicola which we were investigating, except that the eggs, one of which is shown in plate IX., fig. 6, were only three-fourths as large. The structure of the worm was the same in every particular, the embryological development was similar, yet every egg of the thousands in the lot had the unusually small size. Shall this be considered a distinct species? If not, then we can see no reason for considering Heterodera radicola as a distinct species from H. Schachtii, until actual comparison shall show them to be so, on characters not yet established.

NOTE.—Since the above was written there has appeared a bulletin on the cotton plant from the Office of Experiment Stations, U. S. Department of Agriculture, in which, under the heading of diseases of the cotton plant Professor Atkinson has briefly described the nematode root gall disease. In describing the structure of the male worm he speaks as follows: "Occasionally some males were found which showed but a single testis. Since Heterodera Schachtii possesses but a single testis, it might be well to inquire whether that species was also present and whether they are associated in the same roots in some cases or whether there is a variation in H. radicola in the possession of paired and single testes."

This statement has a very important bearing on the question as to the relations between H. Schachtii and H. radicola in that it casts a doubt upon the only distinctive feature between the species which has been presented. If the first hypothesis be true; namely that both species are present in this country as distinct species, then it would be natural to conclude that our species is H. Schachtii while that studied by Atkinson in Alabama in 1883 was H. radicola. The almost absolute agreement of our results in detail, however, leaves but little doubt that we had the same species to deal with. If the second hypothesis, that "there is a variation in H. radicola in the possession of paired and single testes," be correct, then the separation of the species on this character loses its value completely. We feel, therefore, all the more certain that Heterodera Schachtii and Heterodera radicola are one and the same species.

PART II.

Nature of the Problem in Controlling Nematodes.

The problem of nematode control is not the same in all latitudes or in all countries but is determined by the nature of the conditions which practical growers have to deal with. In the Southern States and in those countries in which the winters are mild nematodes can exist in the soil during the whole winter without any detriment, whereas in the latitude of New England where the winters are cold and prolonged the parasitic form Heterodera cannot survive. As a result of this the parasitic species, the Heterodera, finds its proper habitat in the greenhouses where the soil is kept from freezing and it also survives the winter to a large extent in unfrozen manure heaps. This statement does not hold, however, with the non-parasitic species of nematode, inasmuch as these forms or at least their eggs are capable of standing an exceedingly low temperature and we have never failed to find them in all kinds of garden soil, or, in fact, in any soil which contains abundant decomposing organic matter. These non-parasitic forms are frequently found in decaying vegetables of all sorts and we have many times observed them in the laboratory on decaying matter which had evidently been subjected to no source of contamination except ordinary water from the faucet. The fact that Heterodera cannot stand our New England climate greatly simplifies the problem of controlling nematodes, for here we have the problem confined to our greenhouses and manure heaps and not to hundreds of acres of soil as is the case in the milder climate of Europe and that of the Southern States. Heterodera, however, does occur occasionally in some of our outdoor plants but such cases are always where the plants with their contaminating soil have been removed from the greenhouses as in the case of violets, etc., or else where nematode infested manure has been applied to the soil. It must be evident, therefore, that any rational treatment pertaining to nematodes must take these facts into consideration and must especially bear in mind the sources of contamination. Then again we must pay some attention to the life history of nematodes in order to be successful in controlling them. We have already shown that nematodes propagate by eggs and any method which fails to destroy these is of little account. Could we succeed in ridding badly infested soil of adult nematodes it would only be a matter of one or two weeks before the soil would be swarming again with nematodes ready to attack their proper host. Our experiments both in the greenhouse and laboratory have repeatedly demonstrated this, and this fact is interesting as showing how badly infested soil may become with nematode eggs. It is very clear that any remedy which is to be applied to the soil for the purpose of completely ridding it of nematodes must be one which will not only kill all of the worms but their eggs as well. It is, in fact, the eggs of the nematode which constitute the most difficult factor in their control as they are surrounded by a more or less impenetrable membrane and we have not as yet discovered any solution capable of destroying them in the soil which can be employed cheaply and effectively without injury to the crop.

Plants which are Subject to Nematodes.

The plants which are subject to nematode ravages are quite numerous and they represent a great many different families. Prof. Kühn[1] in 1881 gave a list of 180 European plants belonging to 35 different families which nematodes attack and this list has undoubtedly been enlarged since that time. The most susceptible families according to Kühn's list are the Gramineae (Grasses) in which there are recorded 46 species of plants subject to nematodes, while the Leguminosae (Clovers, etc.) is represented by 33 species, the Compositae (Aster, etc.) by 16 species and the Cruciferae (Mustards, etc.) by 14 species. Neal in his work entitled "The Root-Knot Disease of Plants" has enumerated over 60 species of plants in Florida susceptible to the attacks of nematodes, and Atkinson (l. c.) has listed 36 different plants observed by him in Alabama.

In our Northern States the number of plants attacked by nematodes is very much smaller and is almost entirely confined to greenhouse species. In the North the greenhouse cucumber, tomato, violet, rose, and cyclamen constitute the most important host plants, although they are not infrequently found causing considerable damage to other well known greenhouse plants such as coleus, spinach, heliotrope, fern, moon flower, begonia,[2] and clematis.[3]

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[1] Die Ergebnisse d. Versuche z. Ermittelung d. Ursache d. Rübenmüdigkeit u. z. Erforschung d. Natur d. Nematoden. p. 120, 1881.

Halsted[4] has also called attention to the occurrence of nematodes in the leaves of coleus, chrysanthemum, lantana, bouvardia, begonia, pelargonium, salvia, zinnia and ficus comosa, where they give rise to decomposed spots in the leaves which finally result in their falling off, and giving the plant a generally unhealthy appearance. Halsted has also observed them in the oat in New Jersey, and Sturgis[5] has found them doing considerable harm on the roots of outdoor asters. From the large list of plants attacked by nematodes belonging to numerous and widely separated families it would seem that almost every family under peculiar circumstances might be subject to them. Nematodes normally have a choice in their host, but when this is not present they will attack other plants which apparently seem uncongenial to them. Instances have come under our observation where a crop of lettuce which had been preceded by a crop of nematode infested cucumbers was profusely covered with nematode galls. This, however, in our experience is exceedingly unusual although we are aware of the fact that Kühn gives the lettuce in Germany as one of their host plants. We have, however, grown many crops of lettuce in infested soil without ever finding a gall upon their roots.

Amount of Damage Caused by Nematodes.

When we take into consideration the large number of host plants subject to nematode attack and the economic value of these plants, the losses caused by them must be enormous. The losses, however, are much more severe in those countries where the winter is mild than in colder climates where the nematodes are practically confined to greenhouses. In Europe the greatest loss occurs to sugar beets and in our Southern States the damage done to all kinds of fruit trees and garden truck amounts to considerable. In regard to the extent of the losses caused by nematodes to our economic plants we can do no better than quote Dr. N. A. Cobb, (l. c., p. 179) Pathologist to the Australian Government, who has made an extensive study of this whole group of worms from various parts of the world. He states "The extent of the damage done by gall-forming worms is difficult to estimate. Much land in Europe has become so badly infested that certain crops—for example, sugar beets—have to be abandoned altogether. Not a beet root will mature. The plants break the ground, languish a few weeks and then die. Were it possible to sum up in pounds, shillings and pence the damage done (by nematodes) the total would probably amount to a fortune for a nation."

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[2] Selby, Ohio Agr'l Exp. Station, Bull. 73, p. 228.

[3] Comstock. Garden and Forest, Vol. III., p. 59.

[4] N. J. Agr'l Exp. Station, Fifth Annual Rept., 1892. p. 385. See also Garden and Forest, Vol. III. and IV.

[5] Conn. Agr'l Exp. Station Report. 1892, p. 45.

In Massachusetts the greatest loss is experienced in the raising of greenhouse cucumbers. The comparatively soft, tender tissues of the cucumber offer little resistance to their attacks, and while the plant is not always killed outright the vines are weakened to such an extent that the crop is greatly diminished. The amount of damage done to tomatoes is not so severe according to our experience as that done to cucumbers, as tomatoes possess a firmer tissue than the cucumber plant and for this reason appear to suffer much less from nematode attacks. The roots of roses, however, are frequently nematode ridden and the result is always disastrous as is evidenced by their generally weak condition and lack of foliage. Violets are also commonly affected with nematodes, and they are undoubtedly the direct cause of many of the difficulties with which violet growers have to contend. One of our correspondents, an intelligent and experienced gardener, writes as follows upon this subject: "After quite a little deliberation I have come to the conclusion that one-half of the trouble in violets is due to nematode worms either in a direct or indirect manner, viz., leaf curl in violets may be direct, by the paralysis of the roots due to the action of the worm, and violet spot is indirectly caused by insufficiency of nutriment to the leaf, causing it to be weak there and immature, thus making it an easy prey to fungous diseases." Nematodes are found less often upon cyclamens and other greenhouse plants, although when they are abundant they give rise to unhealthy conditions in the plant which are not easily overcome and which greatly affect the beauty and value of it.

A Review of the Various Remedies which have been Applied for Nematode Repression.

a. TREATMENT BY CHEMICALS.

In considering the effects of the application of chemical substances to the soil it must be borne in mind that we have to deal with quite a different matter from that of applying fungicides or insecticides to the surface of a branch or leaf. In the case of a leaf or branch we have organs which are more or less protected with a cuticle, thus rendering them to a large extent impervious to solutions which in the case of roots where absorption of nutrients is one of the principal functions the effects are much more injurious. It is well known to physiologists that the roots of a plant constitute one of the most sensitive and irritable organs with which we have to deal, and it does not require a very strong solution of any substance in the soil to produce abnormal conditions in the plant. The nutritive solutions contained in the soil which the plant utilizes for its food are always exceedingly dilute and even when slightly concentrated by excessive manuring, or by the use of an improperly proportioned and too concentrated fertilizer they greatly injure the plant. Indeed those pathologists who have an extensive opportunity to observe sickly plants not infrequently have to deal with disorders due entirely in the first place to improper feeding, although the gardener may surmise that the trouble is brought about by some insect or fungous pest which may be associated with his plants merely in a secondary manner. What applies to the excessive use of normally nutrient substances would apply with greater force to substances which do not constitute the food of plants and some of which are known to be quite poisonous to them. Chemical solutions for the killing of nematodes in the soil would have to be applied in a very concentrated form and in considerable quantities in order to be effectual, although some experimenters have advocated the homeopathic method of applying remedies. Various chemical remedies, however, have been recommended, many of which have been tried with reported success. These have been applied both in solutions and in a solid form, either upon the soil before planting, or after the plants were set out. Some of those employed by various experimenters are as follows:—Potassium permanganate, Sulfate of Manganese, Tobacco dust, Tobacco decoction, Unslaked lime, Carbon bisulfide, Kainit, Ammoniacal liquor from gas works, Ammonium sulfate, Potassium chloride, cyanide, sulfate, and sulfide, Nitrate of Soda, Sulfate of Zinc, Lye, Hyposulfite of Soda, Carnallit, Potassium sulfocarbonate and xanthogenate, Sulfate of Iron, Unleached Ashes, Carbolic Acid, Gasoline, Naptholine, Kerosene Emulsion, Arsenates, Muriate of Potash, Sodium chloride, Sodium sulfocarbonate and xanthogenate, Sulfur, and Calcium sulfate. Neal, (l. c.) who employed a large number of chemicals, obtained negative results with almost everything. He found, however, that the alkaline solutions gave more encouraging results than any other and tobacco dust mixed with Kainit also worked well.

Professor Kühn who has worked upon the problem of nematode control for many years has experimented with a great variety of chemicals of different strengths. He found no chemicals, however, that would control nematodes, although the use of some has shown partial benefits.

Ammoniacal liquor from gas works was recommended by Villet[1] who claimed that it destroyed nematodes and acted as a fertilizer at the same time.

Lye was recommended by Comstock[2] as a wash for greenhouse benches before renewing the soil.

Watering rose plants affected with galls with a solution of lime water or soda was advocated by May[3], although he subsequently found that even when Nitrate of Soda was applied as strong as 1 oz. to 4 gals. of water (1-500) it failed to kill nematodes.

Bailey[4] tried concentrated commercial lye, common salt, lime and Carbon bisulfide on pots of infested soil in which tomatoes were planted. These experiments were upon a small scale and while he obtained galls on all of the plants except the one which was treated with salt at the rate of 2 lbs. to a pail of water he does not consider them conclusive.

Halsted[5] calls attention to the use of lime either by sprinkling it upon the soil or by plowing it in.

Selby (l. c.) experimented with potash salts such as Muriate of Potash and Kainit and also Manganese sulfate, Potassium permanganate, lime water and air-slaked lime, but with the exception of a slightly accelerated growth produced by the use of some of the above named solutions he obtained entirely negative results.

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[1] Rev. Scient. ser. 4, 1895. No. 1, p. 27.

[2] Garden and Florist, Vol. III., p. 59.

[3] American Florist, 1896, p. 649, also 1897, pp. 770-771.

[4] Bulletin 43. Cornell University, Agr'l Exp. Station, 1892.

[5] New Jersey Agr'l Exp. Station Report, 1892, p. 384.

Hollrung reports some experiments with potash salts such as Kainit, Carnallit, and Potassium chloride. The results obtained were rather inconclusive but seem to show that potash salts while having a palliative effect must not be considered as specifics for nematode repression.

Many European investigators have tried potash salts of various kinds upon soil for the repression of nematodes. The literature giving the results of their experiments seems to agree that more beneficial effects have been obtained from their use than any other. On the other hand Dr. Max Hollrung[1] who has experimented extensively for a number of years on the beet nematode and who has had opportunity to try a great variety of methods and chemicals, claims that potash salts in amounts in which they can be used as fertilizers are not capable of destroying nematodes in the soil, and that the beneficial effects of potash salts in such soils are due to other chemical and physical causes. Some sugar beet experimenters have advocated the use of good fertilizing together with the practice of planting early. They claim that by this method sugar beets can be started at a time when they are likely to be less attacked by nematodes, as the plants can thrive even when it is too cold for the nematode to be active and consequently less loss will be experienced by their ravages. In regard to the efficiency of chemicals it must be borne in mind that there are probably no instances where soil has been completely rid of nematodes by this means, although in many instances better crops have been produced after their application.

Various methods of treating nematodes have been practiced for a great many years in Europe, and a considerable amount of literature has already made its appearance relating to this subject. Many methods have been recommended and tried only to find that they were not in every instance sure and practical, and these in turn have been followed by others which have promised better results.

One thing, however, appears to be certain, that many of these remedies have only been given a superficial trial. Had the case been otherwise, many of the remedies advocated would have become obsolete long before this. Instances have occurred where experiments have been carried on by the use of similar remedies which have given exactly opposite results. It must be borne in mind that it is impossible to draw reliable deductions from experiments which have been tried only once or twice upon a small scale. Especially is this true in regard to nematodes, as they normally manifest different periods of activity. We have observed instances where nematodes have disappeared from soil where no treatment has been applied and under circumstances which rendered their disappearance not easy of explanation. Upon this point it should be remembered that we do not as yet fully understand all of the environmental conditions which play a role in their life history, and for this reason we are more likely to fall into errors in interpreting results from experiments. Our own experiments which were very extensive have convinced us that the application of chemical substances to the soil is of little practical value in ridding it of nematodes.

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[1] Zeitsch. landw. Cent. Ver. Sachr., 1892. No. 12.

(b).—THE DESICCATION METHOD.

It is well known that drying is very destructive to nematodes and we have repeatedly seen the effects of this in our laboratory and greenhouse. Vahne* who has advocated this method of treatment takes advantage of a long dry spell of weather, either in the fall or spring, and by working the soil repeatedly with plows and cultivators, thus giving it a chance to become as dry as possible, claims to have succeeded in making it an uncongenial habitat for the worm. After the drying process is partially completed he applies unslacked lime at the rate of 2-4 tons to the acre which assists further in the desiccation of the soil and destruction of the worm. He has tried this method with reported success upon fields where sugar beets were planted, and he further maintains that it is efficient as a remedy for certain parasitic fungi such as the damping fungus (Pythiun de Baryanum) Leaf spot of beet, (Phoma Betae) etc. This method is undoubtedly a very cheap one of controlling nematodes provided it works satisfactorily, although it must be difficult out of doors in a variable climate to always find the right season for its application. We have frequently found that drying small masses of soil in the greenhouse for a number of weeks completely rids the soil of nematodes but we have no data in regard to this method when carried on upon a large scale. We have, on the basis of our own experiments, frequently advised cucumber growers who were troubled with nematodes, to try this method on a more extensive scale than we could. But as yet we have received no reports. Most of our cucumber houses lie idle long enough during the summer to give this method a more thorough trial than is possible out of doors, inasmuch as greenhouse soil is not subject to occasional drenchings from rain and consequently the drying can be carried on to a much greater extent. This treatment is so simple that it is hoped reliable data may be furnished ere long.

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*J. Vahne, Zur Frage d. Vetilgung v. Nematoden aus schadlichen Pilzen im Boden, Wiener landw. Ztg. 1897, p. 732.

(c).—THE HALLE OR CATCH CROP METHOD OF DESTROYING NEMATODES.

The method of treating nematodes other than by chemicals was originated and employed some years ago by Dr. Julius Kühn of the University of Halle, Germany, and it has since been extensively tested by Dr. Kühn and his colleague Dr. Hollrung, both of whom have spent some years in investigating the nematode pest in connection with the sugar beet industry. In 1896 we visited Halle and examined the work done at this institute, and we wish here to express to Dr. Max Hollrung our appreciation of the many courtesies shown us while there.

The parasitic nematode (Heterodera) is widely distributed and very injurious to the sugar beet in Europe and any method which endeavors to control it must be one which can be applied cheaply, on account of the large area which it is necessary to treat. The method employed is based upon the knowledge gained from a study of the life history of the organism. It has been shown by Strubell that the worm on entering the beet develops its young in the course of six weeks, and Kühn taking advantage of these facts reasoned that, if the infested host plants could be dug up and destroyed before the worms laid their eggs, the soil could be rid of a large number of worms. His method, therefore, consists in trapping the worm and is popularly known as " The Catch-crop Method ", and for the succesful carrying out of this idea in treatment he made use of a host plant especially susceptible to Heterodera, generally a species of mustard (Brassica Rapa rapifera, Metzg.) which he sows on the soil in the spring. The nematode attacks the mustard, gains entrance to the root, and locally stimulates the plants to produce galls. About the time the roots of the mustard become well covered with galls, which is an indication that the worms are confined within the tissues of the host, and before they have laid their eggs, the roots of the mustard are plowed up and are either exposed to the drying rays of the sun or are raked up and burned. In this way the catch-crop method not only destroys a great many nematodes contained in the infested soil, but also hundreds of eggs, which if left would in a short time give rise to innumerable adult worms. Dr. N. A. Cobb (l. c. p. 170.) states that the female nematodes lay from 300-400 eggs, and when we consider that some galls are one inch or more in diameter and contain numerous females the crop of young must be enormous. We have frequently obtained hundreds of them when only two or three females were introduced. By continual planting catch crops in the soil the nematodes can be reduced to a considerable extent, as the experiments of Kühn and Hollrung seem to show, but it is impossible to completely rid the soil of the worms. Such a method might be of some value in our Southern States where the nematodes are very abundant and attack a large variety of cultivated plants, but in the north, where the Heterodera cannot stand our winter climate and where they attack almost entirely greenhouse plants, more effective remedies must be sought.

The Effect of Chemicals upon Nematodes.

Our first experiments relating to the control of nematodes were largely along the line of many of those we have just described, that is to say we endeavored to find some chemical method of control. The problem confronting us was to be sure somewhat different from that confronting those having large areas of infested soil out of doors with which to deal. Granting that the chemical method of treatment might be more or less successful out of doors, we ought nevertheless to require some more absolute method in greenhouses, because there is much less area of soil there to be treated and it is under conditions which can be more readily controlled. Nevertheless we made many hundreds of experiments with chemicals in order to give them a thorough trial and to see if such a method of treatment was practical. We carried on our experiments simultaneously in the laboratory and in the greenhouse which were connected with each other. Parts of the greenhouse had been devoted to nematode work for over three years and the space devoted to the purpose was large enough to pursue our experiments to advantage. In general, however, the solutions were tried in the laboratory first to see what effect they would have upon the adult worm. For this purpose numerous cultures of nematodes were kept on hand. In order to test the various solutions upon them we employed hollow glass slides placing the worm directly in the solution, and where volatile solutions were used we utilized what is known as the Van Tieghem drop culture chamber which consists of a glass cylinder about $\frac{3}{4}$ in. in diameter, having a capacity of about 3cc., fastened to an ordinary slide. This gave us a tight moist chamber in which the nematodes were suspended in a drop of water on the under side of the cover slip, the volatile solution being placed in the bottom of the chamber. The number of nematodes selected for treatment varied anywhere from 5 to 100. The experiments were confined entirely to the adult worm* and not to the eggs of the nematode which were, however, sometimes present. In some instances the solutions were made up from pure chemicals, in other instances commercial chemicals were used. The following table shows the various experiments made in the laboratory with chemical solutions of different strength.

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*Note. In these experiments various free living species of nematodes were used.

TABLE SHOWING THE EFFECTS OF VARIOUS STRENGTHS OF CHEMICAL SOLUTIONS UPON ADULT NEMATODE WORMS.

Solution.	Strength of solution.	Time of observation.	Results.
Manganese sulfate,	1-250	9 days	alive.
	1-100	18 hrs.	alive.
Common salt,	1-250	2 days	alive.
	1-100	52 hrs.	alive.
Potassium nitrate, c. p.,	1-250	52 hrs.	alive.
	1-100	52 hrs.	alive.
Magnesium sulfate, c. p.,	1-100	6 days	alive.
Calcium sulfate, c. p.,	sat. sol.	24 hrs.	alive.
Kainit,	1-250	5 hrs.	alive.
	1-100	52 hrs.	alive.
		10 days	alive.
Sodium nitrate, c. p.,	1-100	52 hrs.	alive.
Potassium sulfid,	1-100	3 hrs.	alive.
	1-50	1-2 hr.	alive.
Hydronapthol,	1-2000	96 hrs.	alive.
Tobacco decoction,		18 hrs.	alive.
Ammonia sulfid,	1-100	3 hrs.	alive,
Potassium permanganate,	1-100	3 min.	most all movement ceased.
		10 min.	all dead but two.
		35 min.	all dead.
	1-200	3 hrs.	dead.
	1-250	4 hrs.	dead.
	1-400	1 hr.	slight movement.
		4 hrs.	apparently dead.
	1-500	18 hrs.	dead.
	1-800	5 hrs.	some living.
		24 hrs.	all dead.
	1-1000	24 hrs.	dead.
Lime water (slacked),	sat. sol.	24 hrs.	alive.
Lime water (air slacked),	sat. sol.	24 hrs.	alive.
Lime and sugar equal parts, (saccharate of lime),	1-100	30 min.	dead.
	1-40	30 min.	dead.
	1-20	30 min.	dead.
	1-10	3 min.	dead.
Caustic potash (crude),	1-100	18 hrs.	alive.
Ammonia, c. p. (vapor),	1-100		killed instantaneously.
Benzole (vapor),	full str.	1 min.	all succumb.
Ammonia, com'cial (vapor),	full str.	2 hrs.	slightly quicker than benzole.
	1-100		dead.*
Ammonia water (vapor), (from gas works),	full str.	1 min.	all succumb.
	1-5	5 min.	all succumb.
Potassium sulfid,	1-100	1 1-2hrs	alive.
Formalin (commercial),	full str.	7 min.	dead.
Carbon bisulfid,	full str.		died instantaneously.

***The exact time was not observed at which they all succumbed.**

From these experiments it will be readily seen that there are many solutions that will kill the isolated nematode instantly, and there are many other solutions that have apparently no effect upon them when left in the solution for a number of days. Those solutions that are volatile and which give off a penetrating vapor are the most effective as nematode destroyers, such for example as Carbon bisulfid, Benzole, Ammonia, Formalin, and Ammonia water from gas works, the latter solution besides containing Ammonia, possesses many of the coal tar products and has some value as a fertilizer when used in dilutions. The most effective solutions applied were Potassium permanganate, Lime and Sugar, (Saccharate of lime), and Potassium sulfid. The first named solution 1-200 killed all nematodes in three hours and this strength of solution can be applied to the plants without injury to them. The lime and sugar was made as follows: 5 grms. of lime were slacked in water and to it was added 5 grms. of sugar to which was added 100 cc. of water, thus making practically a 10% solution or 10-100. For more accurate purposes the degree of alkilinity could be employed as a basis for the solutions. This was reduced to various proportions. In a saturated solution of slacked lime water the worms were alive and apparently well after 24 hours. This experiment was not continued as it was thought to be useless. In a solution of 1-250 Manganese sulfate they thrived 9 days and similar results were obtained with common salt, Potassium nitrate, Magnesium sulfate, Kainit and Sodium nitrate. Hollrung also experimented with solutions of Kainit, Carnallit, Chlorid of Potassium and Sulfate of Potash in a similar way. He employed different strengths of solutions which were as follows 0.1%, 0.5%, 1.0%, 2.5% and 5.0%, or 1-1000, 1-200, 1-100, 1-40, and 1-20, and examinations were made at different periods ranging from 5 minutes to 96 hours. He concluded that these solutions were not capable of being used as a remedy for nematodes.

Most of the solutions enumerated in the preceding table were also tried upon cucumber plants in the greenhouse which were planted in nematode infested soil. As a rule the pots employed were 10 inch ones and numerous seeds were sown in each. The roots of the seedlings were examined from time to time with the naked eye and also with the microscope to ascertain whether nematodes were present and the amount of infection to which they were subject. The following table shows the results in a condensed form of only a few of the experiments made along these lines. The name of each solution tried is given in the first column, and the strength of the solution, the amount applied, and the size and number of pots are also given.

The strengths of the solutions are given in proportion as in the previous table, for example, 1-200, which indicates that one part of the solution was used to 200 parts of water or practically a 0.5% solution.

While the experiments with chemicals given in this table constitute only a few of the many which we have made, they are nevertheless representative as far as reaching any positive results are concerned. In fact the solutions given in the table are those which in our laboraatory experiments appeared to give the most promising results and as we have already pointed out some of them have been recommended by other experimenters. From the many hundreds of microscopic examinations of the young cucumber roots and previously infested soil in which they were growing there can be no doubt but that some of these solutions when applied quite strong and in considerable quantities are capable of killing many of the adult worms in the soil. We have repeatedly found many dead nematodes in the soil after applying large amounts of Potassium permanganate of the strength of 1-200 or 1-300, or of Potassium sulfid at the rate of 1-250, etc., and all of the experiments with Carbon bisulfid, commercial Ammonia, and most of those with Ammonia water from gas works showed the same thing. The remaining solutions appeared to have no effect upon the adult worms at the strengths at which we used them and even where we covered the surface of the soil with lime to a depth of $\frac{1}{8}$ inch and watered the same with a saturated solution every few days, nematodes were abundant in the soil. Evidently the most effective solutions for the worms were Carbon bisulfid and the two Ammonia solutions. The killing of a few adult worms in the soil, however, is of absolutely no consequence. As long as the nematode eggs are present a new crop of large proportions can be expected within a few days. The solutions appear to have no effect upon the eggs because they are protected by an almost impervious coating. Dr. N. A. Cobb states that the young embryo is well protected in the shell and can withstand very strong poisons.

TABLE SHOWING THE EFFECTS OF SOLUTIONS UPON NEMATODE-INFESTED EARTH IN WHICH CUCUMBERS WERE GROWING.

Solutions.	Strength of solution.	Amount applied to each pot.	No. of pots employed.	Results.
Potassium permanganate,	1-200	700 cc.	6 10-in.	Negative.
	1-250	800 “	6 “	
	1-500	800 “	6 “	
	1-750	800 “	6 “	
	1-1000	800 “	6 “	
	1-300	800 “	8 “	
	1-250	2500 “	1 “	
Kainit,	1-200	800 “	6 “	Negative.
	1-200	800 “	6 “	
Manganese sulfate,	1-200	800 “	6 “	Negative.
	1-200	800 “	6 “	
Potassium sulfid,	1-250	250 “	4 7-in.	Negative. 1-100 injured the plants.
	1-200	250 “	2 “	
	1-100	250 “	2 “	
Slacked lime water,	saturated sol.	applied freely,	4 “	Negative.
Nitrate of soda	1-150	500 cc.	4 “	Negative.
Ammonia, (commercial),	1-100	250 “	2 10-in,	Negative.
	full strength,	10 “	2 “	Negative. Solution applied before planting.
	“ “	15 “	2 “	
	“ “	25 “	3 “	
Carbon bisulfid,	“ “	5 “	6 “	Negative. Solution applied before planting.
	“ “	10 “	6 “	
	“ “	15 “	6 “	
	“ “	20 “	6 “	
	“ “	30 “	2 “	
Ammonia water, (gas works),	“ “	10 “	6 “	Negative. Solution applied before planting.
	“ “	20 “	6 “	
	“ “	25 “	8 “	
	“ “	40 “	6 “	
	1-4	800 “	12 “	Negative. Solution applied after planting. 1-3 and 1-4 injured the plants.
	1-5	800 “	9 “	
	1-6	900 “	6 “	
	1-8	800 “	6 “	
	1-3	150 “	1 “	

Plate X. illustrates the result of one experiment which bears upon this point. The photograph was taken in our experiment house and shows six pots with dead immature cucumber plants in them which were set out at the same time as the other robust uninfected plants shown at their right and left. In this experiment two of the pots received before planting 30 cc. of Carbon bisulfid each; two also received 30 cc. of Ammonia water from gas works; and two pots were treated with 2100 cc. of Potassium permanganate at the rate of 1-300. The Potassium permanganate pots were again treated twice some days afterwards with the same amount and strength of solution except that the last treatment was at the rate of 1-250. Microscopic examinations of the soil after treatment showed many dead worms, but ten days afterwards when the young cucumbers had already appeared, an examination of the soil showed abundant nematodes, and galls had commenced to form profusely upon the roots. The cucumbers in each of the six pots were in badly infested earth and none of them ever lived to be more than 15 inches in height, and notwithstanding the fact that each pair of pots received different treatments of a severe nature there was no choice between the plants a few weeks later. Such results as these demonstrate the futility of attempting to treat nematodes by chemicals, for here we had them confined to pots, or in other words to narrow limits and under the most favorable conditions for exterminating them. Even should this treatment have proved successful the amount of solution which would have to be applied to open soil on a large scale would be costly. Almost all solutions when applied to the soil in considerable quantities are harmful to the plants. Potassium permanganate appears not to injure plants as much as one would suppose. We have applied at a single time 2500 cc. (over two quarts) of this solution at the rate of 1-250 to a 10 inch pot of earth containing cucumbers, without the slightest ill effect. Ammonia water from gas works as we obtained it is injurious when applied even at the rate of 1-6; that is one part of Ammonia water and six parts of ordinary water. Potassium sulfid is more injurious to plants than Potassium permanganate and a mixture of Sugar and Lime even when considerably reduced is quite injurious; although Lime itself causes no harm to cucumber plants and is sometimes used by practical growers to improve their soil. Carbon bisulfid was applied to the soil usually before the plants were set out. This was done as follows : a hole was made with a stick in the soil reaching nearly to the bottom of the bed, or pot if such happened to be used, into this was inserted a funnel to catch the liquid and convey it to the bottom of the hole, after which the funnel was removed and the top of the hole was stopped up with earth. The fumes from the very volatile liquid soon permeate the soil and in this way many worms are killed. It was not possible, however, to apply much of this solution to pots containing cucumber plants, as we found that they were invariably injured even when as small a quantity as 15 drops were used, although in the open soil it can be employed with much less injury to the plants. Commercial Ammonia and Ammonia water from gas works were usually applied in the same way as was the Carbon bisulfid, although neither of them at the concentration used caused any injuries to cucumber plants.

From the experiments with solutions we may draw the following deductions :—

There are many solutions capable of killing a certain percentage of adult worms that can be applied to the soil either before or after planting without injuring the plant. The strength and the amount of the solution necessary to kill the adult worm in the soil is considerably greater than that necessary to apply when the worm is isolated. This is due to the difficulty in getting the solution to come in contact with each particle of matter in and around which the nematodes thrive. None of the solutions named above are capable of killing the eggs of the nematode in the soil, and unless this is accomplished the treatment is of no account.

Sterilizing or Heating the Soil the most Effectual and Practical Method of Exterminating Nematodes in the Greenhouse.

Our experiments in heating the soil by means of steam for the control of nematodes have been carried on for three years. At the outset we did not happen to know of any practical method of heating soil with steam—neither did we consider it wise to experiment too extensively along this line until we had obtained more knowledge of the efficiency of chemicals upon nematodes. Subsequently, however, we learned of some investigations being made by B. T. Galloway[1] of the U. S. Dept. of Vegetable Pathology on the effects of heating soil by steam for the purpose of ridding it of violet nematodes, and this led us to make more extensive trials of the steam heating method. While our experiments upon sterilizing[1] the soil were well under way there appeared Bulletin No. 73 of the Ohio Station[2] which gave some account of sterilizing the soil for the nematodes on cucumbers. It appears from this bulletin that Mr. Lodder, a practical cucumber grower in Ohio, who had experienced severe losses from nematodes reported favorable results from the use of steam. In looking up the matter further we also found that a Mr. W. N. Rudd[3] had earlier employed a method similar to that described above with favorable results. More recently Mr. J. N. May[4], a large rose grower, has described a method which he has used extensively for sterilizing his soils to rid them of nematode worms. Mr. May's heating is done on a large scale and it would appear to be a practical method of treating nematodes even when carried on in connection with a large range of houses. Our own experiments along this line have demonstrated that as far as greenhouse culture is concerned the method of sterilizing the soil by means of steam for the purpose of ridding it of nematodes is at the present time the most practical method which can be employed, although it is not at all improbable that some other cheaper method may yet be found.

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[1] For description see American Gardening Vol. XVIII, 1897 p. 127.

Amount of Heat Necessary to Kill Nematodes and Their Eggs.

From the account given by Mr. May it would appear that considerable heat is required to kill nematodes in the soil. He states that "by the best authorities it is proven that nothing short of 225° F. will kill them (nematodes) when protected in the soil, but to make sure work 235° F. of heat is necessary". In regard to this statement we shall have to take some exceptions and will subsequently show that such temperatures are unnecessary to kill nematodes except under exceptional conditions.

It is well known that a temperature of 212° F. will kill any organism in a short time and in fact the great majority of organisms are killed at much lower temperatures. Again the resistance of animals to heat is not so great as the spores of bacteria and fungi. In the case of nematodes we have not only to kill the adult worm which is not remarkably protected against heat and desiccation, but also its eggs which are able to offer considerable more resistance to the various elements, inasmuch as they are provided with a more protective membrane. Nevertheless there is nothing about the structure of a nematode egg which would render it so impervious to heat as some of the smaller spores which every bacteriologist has to deal with in sterilizing his culture media. If a large mass of soil is heated and the circulation of the steam is irregular through it then it may be necessary to use high temperatures in order to thoroughly impregnate every particle of the soil with steam and thus bring every particle to the same temperature. From a letter which we received from Mr. May we inferred that this was the principal reason for his using high temperatures. Our own experiments upon this point were numerous and they were made with earth containing abundance of nematodes of various species in all stages of development. For the sake of convenience we will designate these experiments as a, b, c, etc. In all of these experiments we employed cucumbers in pots of various sizes, (from 4 in. to 10 in.), and the plants were left until they were sufficiently large to show root galls upon them if nematodes were present in the soil. In every case except "a" the pots containing the infested earth were sterilized in an Arnold steam sterilizer and when moderate heating was required they remained in the sterilizer only a few minutes. The earth in experiment "a" was part of a large lot which was sterilized in a box by means of steam from a boiler. (See fig. II., 1, 2, 3). In every instance numerous microscopic examinations were made of the soil and roots of the plant in order to determine whether nematodes were present. The non-parasitic species are generally present in almost every soil and their presence can very often be suspected by the coloration of the root. They are generally found on the older parts of the root near the surface of the soil as indicated by the dirty brown color of the epidermal tissue. The experiments are as follows:

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[1] Note. While the term sterilizing has been employed by all writers who have described their experiments upon steaming soil, it must be borne in mind that probably in every instance complete sterilization has not been accomplished. We made cultures of soil which had been heated up to 204 F. and in every instance bacteria were abundant.

[2] Ohio Agricultural Experiment Station, Bulletin No. 73, p. 227, 1896. By A. D. Selby.

[3] American Florist, Vol. IX, p. 171, 1894.

[4] American Florist, Vol. XIII, Feb., 1898.

Exp. a. Six 4-in. pots were filled with infested earth which had been heated at 212° F. The pots were also sterilized and the cucumber seed after soaking 12 hours in water was placed for 10 minutes in a saturated solution of corrosive sublimate and before using was rinsed with sterilized water. During germination and the growth of the plants they were always watered with filtered water. Hence all source of contamination was eliminated. Result, no nematodes.

Exp. b. Six plants treated as above. Result, no nematodes.

Exp. c. Twelve pots of cucumbers, the seeds of which were treated as in Exp. "a" and the plants watered with sterilized water. Instead of the soil in the pots all being heated to 212° F. they received the following various degrees of heat before planting:

No. of pot,	1	2	3	4	5	6	7	8	9	10	11	12
Temperature,	114°	118°	127°	140°	147°	150°	159°	161°	163°	163°	170°	176° F.

Result. Nos. 1, 2, and 3 all damped[1] off. The remainder were perfectly free from the damping fungus and nematodes.

Exp. d. Sixteen pots of cucumbers treated the same as "c."

No. of pot,	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Temperature,	147°	149°	154°	159°	163°	167°	168°	172°	176°	183°	185°	186°	192°	194°	196°	199°F.

Result, no nematodes.

From these experiments which only represent about one-half of what was done it appears that a very high temperature is not necessary in order to free infested soil of nematodes. The number of degrees of heat necessary is about 140° F., but as a matter of safety the temperature should go above this inasmuch as in large areas of soil the distribution of heat is always unequal, and while one portion may be heated as high as 190° F. another portion may not exceed 110° F. The conclusion then that the soil must be heated under pressure to a temperature of 225° or 235° F. in order to kill all nematode life is therefore not valid in all cases. These experiments were made with sufficient care and were repeated often enough with the same results to consider them trustworthy. The practice of soaking the seed in a strong solution of corrosive sublimate before planting them was perhaps an unnecessary precaution inasmuch as we have never been able in repeated examinations to find any evidence of nematode infection from this source, but the watering of the pots with filtered water[2] or water which had been previously boiled was quite necessary where we were making observations upon non parasitic species. We have observed many instances of sterilized soil becoming infested with the non parasitic nematodes from the water supply, although we have never detected a case where the parasitic species originated from this source. It is quite likely that the infection comes more often through the nematode eggs contained in the water and less often through the adult worm. The non parasitic nematodes are in general associated with all kinds of decay, and all of our public water supplies which contain decomposing vegetation furnish no doubt an environment for certain species of nematodes. It is not improbable that the high temperatures recommended by some for the control of nematodes were based upon experiments in which care was not taken to prevent contamination, but it is more likely that the large mass of soil employed was not heated evenly and perhaps some portions fell below the requisite degree of temperature. This is more likely to occur where defective methods of piping are employed and also where the soil is piled up to a considerable depth, in which case a thermometer thrust into the top layers of the soil would not always indicate the temperature of some portions underneath.

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[1] The damping fungus in this case was the Pythium De Baryanum, Hesse, which is frequently troublesome to cucumber seedlings.

[2] We used for this purpose an ordinary sand filter which we attached to the faucet.

Methods of Sterilizing the Soil.

Descriptions of methods of sterilizing the soil have not been very numerous up to the present time.

In 1892 Sturgis[1] recommended a method of heating soil for Aster culture. In this case the plants were grown out of doors and the roots became covered with galls probably through the introduction of unfrozen soil or manure which was infested with the worm. It can easily be seen that there are many difficulties in heating soil out of doors to kill nematodes and when attempted on a large scale it would not be practicable nor in this climate necessary, providing proper precautions are taken. Should such a measure become necessary, however, the method advocated by Dr. Sturgis might be employed on a small scale. He recommends the application of a device commonly used for drying earth in the preparation of asphalt pavements. It consists of a large piece of sheet iron 6 or 8 feet square, raised from the ground. A wood fire is built under this and the earth is thrown on and allowed to heat for 10 or 15 minutes. When this is completed the earth is removed and another supply is placed upon it and heated for the same length of time. A considerable quantity of earth can be heated in this way in a single day, but as we have previously stated we question whether for nematodes there is ever any necessity for treating out of door earth, provided careless inoculation of the soil is guarded against. This method of heating would, of course, produce different conditions in the soil from that of steaming. We have never found the dry heating method as satisfactory as the steam method, inasmuch as the former leaves the soil dry and disturbs the mechanical conditions, while the latter method leaves it moist and porous and more suitable for plant growth. The first notice of the application of steam for sterilizing upon a large scale which we have observed is that used by Mr. W. N. Rudd[1] of Mt. Greenwood, Ill. The steam method has probably been used by other growers even before this but we have taken no particular pains to look up this point. Mr. Rudd employed a box 20 ft. long, 6 ft. wide, and 4½ ft. deep, over the top of which he placed some hot bed sash and in the bottom of the box he ran three lengths of 1¼ in. steam pipes which were bored every 18 in. with $\frac{3}{16}$ in. holes, thus allowing the steam when forced in to penetrate through the soil. He does not state the pressure of steam used or the temperature to which the soil reached, but says that when a potato which he usually put in the soil is cooked the earth is ready to be used and that two hours steaming is sufficient for this purpose.

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[1] Conn. Agr. Expt. Station Report, 1892, p. 48.

Mr. Lodder[2] later describes a method similar to that used by Mr. Rudd but with some variation in the details of constructing the box and utilizing the steam. He used a box 20 ft. long, 6 ft. wide, and 5 ft. deep, which sat upon the ground and was provided with a solid bottom and a cover for the top. The floor of this box upon which the soil was placed was raised 1 ft. from the bottom, thus forming a superstructure, and consisted of 1¼ in. steam pipes laid close together which were open at each end presumably for the free circulation of the steam. The main steam pipe passed lengthwise through the box just under the superimposed pipe floor and was 1¼ in. in diameter with ¼ in. openings every foot. The pipes constituting the floor were covered with a layer of straw to prevent the earth which covered them from sifting through. The steam which is let into the pipes soon completely fills the space below the soil and when under pressure passes upwards between the pipes and through the straw, permeating the soil. Mr. Lodder claimed to sterilize the earth in this box, which contained 480 cu. ft., in four hours when a pressure of steam equal to 40 lbs. was maintained, and in three hours when the pressure was equal to 60 lbs.

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[1] American Florist, Vol. IX., p. 171, 1896.

[2] Ohio Agr. Expt. Station, Bulletin No. 73. p. 231, 1896.

Mr. Galloway[1] of the Dept. of Vegetable Pathology, Washington, D. C. has given a brief account of a method employed by him for sterilizing soil infested with rose and violet nematodes. He made use of an ordinary porous 2 in. drain tile instead of steam pipes punctured with holes. The drain tiles are placed in the bottom of a box of any convenient size and connected with a steam pipe leading from a boiler having a high pressure. The box used in his experiment was 12 ft. long, 12 in. deep and 6 ft. wide, filled with soil, and through this three lengths of tile were placed. This was covered with hot bed sash in order to inclose the steam. Such a box will hold 72 cu. ft. of earth and he claims that this amount of soil can be heated in two hours. From the results of our own experiments along this line we feel quite certain that with six lengths of tile in a box of this size instead of three this soil could have been heated in one hour.

Mr. J. N. May,[2] an extensive rose grower, has recently described a method of sterilizing soil which he employs on a large scale. He makes use of two bins, each of which is 12 in. deep, 3½ ft. wide, and 16 ft. long, and which hold together 112 cu. ft. of soil. These bins are provided with covers rendering them as air tight as possible. They are constructed upon the ground which is slightly graded so as to slope in one direction for the purpose of taking care of the condensation in the pipes. At the bottom of the bins are placed a number of steam pipes 1 in. in diameter which are provided with manifolds at each end and which virtually make a coil. Every third pipe is bored upon the side with holes about 15 in. apart. When the soil is put in and the steam is turned on, part of it escapes through the holes in the pipes and penetrates the soil above. The condensation is conducted by the manifolds back to the boiler. When one bed is sterilized it is uncovered and taken away while the other bed, which in the meantime has been prepared, is steamed. By this method Mr. May empties five or six bins in a day, but to accomplish this he states that it is necessary to have a boiler of some 25-horse power carrying at least 50 lbs. pressure of steam continually. These are the only methods for sterilizing soil, so far as we are aware, that have been described, and all of these methods have been described within two or three years.

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[1] American Gardening, Vol. XVIII, p. 127, 1897.

[2] Sterilizing Soil for Destroying Eel Worms. American Florist, Feb. 5, 1898.

In our experiments[1] relating to soil sterilization we have tried many methods and found the tile system as used by Galloway cheap, and satisfactory for many purposes, especially when we wish to sterilize the soil in the bed in which the crop is to be grown. Another advantage which it possesses is that it can be used for subirrigating purposes. To ascertain the best method of using tile we arranged them in beds of equal size containing the same amount of similarly prepared earth. The beds were 18 ft. long, 30 in. wide and 1 ft. deep and each contained 45 cu. ft. of soil suitable for growing cucumbers. Part of the soil had been used previously for cucumbers and tomatoes and was well infested with nematodes, and previous to sterilization it was mixed with fresh horse manure. The beds contained a different number of feet of pipe which were laid in various ways and in each case they were placed about 2 in. from the bottom. For details concerning the manner of piping see fig. I., a, b, c, d, e. Bed (a) was piped with two lengths of tile without any end connection. Bed (b) was piped with three lengths of tile with end connections, thus forming a continuous circuit. Bed (c) was piped with two lengths of tile with end connections and cross tile every two feet. Bed (d) was piped with three lengths of tile as in (b). Bed (e) was not piped at all. Each bed was treated separately from a 4-horse power portable boiler having a pressure of steam varying from 40 to 80 lbs. The steam was conducted from the boiler through a half-inch pipe provided with a valve, and this led into a 1 in. pipe, (fig. I., 1), which had a four way connection, the ends of which were inserted into the free open ends of the tile. The connections were easily made with the boiler and when one bed was sterilized it was disconnected and the pipe attached to another bed. The steam was confined by means of boards placed over the top, although straw mats or blankets would have served the purpose better. The valve regulating the amount of steam from the boiler was never turned on more than half way, this being found sufficient to supply

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[1] See Nematode Worm and Root Gall on Cucumbers and Tomatoes, New England Farmer, Feb. 26, 1898.

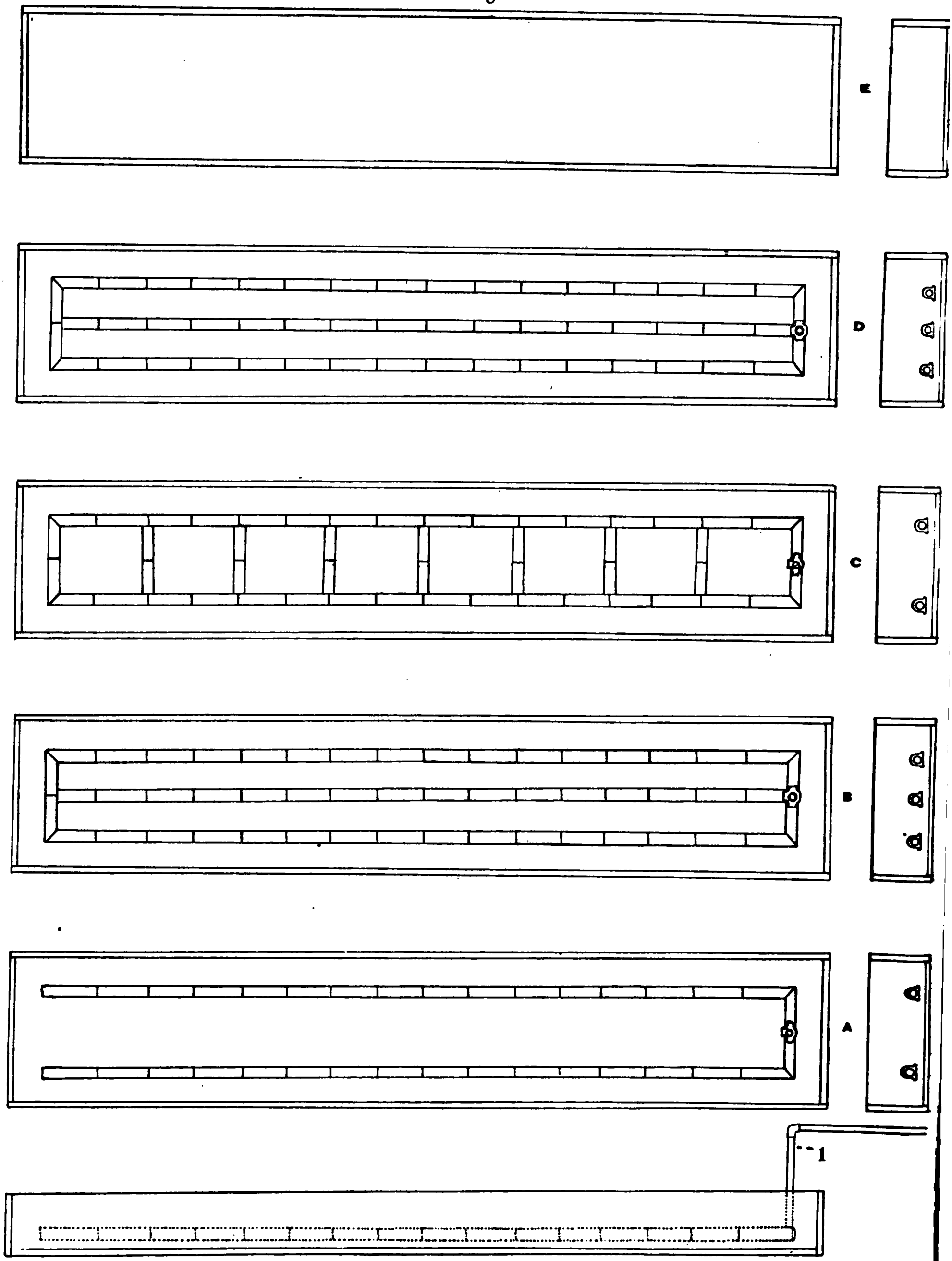


Fig. I Showing the arrangement of piping beds with 2 in. tile. The beds are 18 ft. long, 2½ ft. wide and 1 ft. deep. The tile are placed about 2 in. from the bottom and the various methods of arranging them are shown in cross and vertical section.

all the steam required, and it was, moreover, necessary in using so small a boiler in order to keep the pressure of steam high.

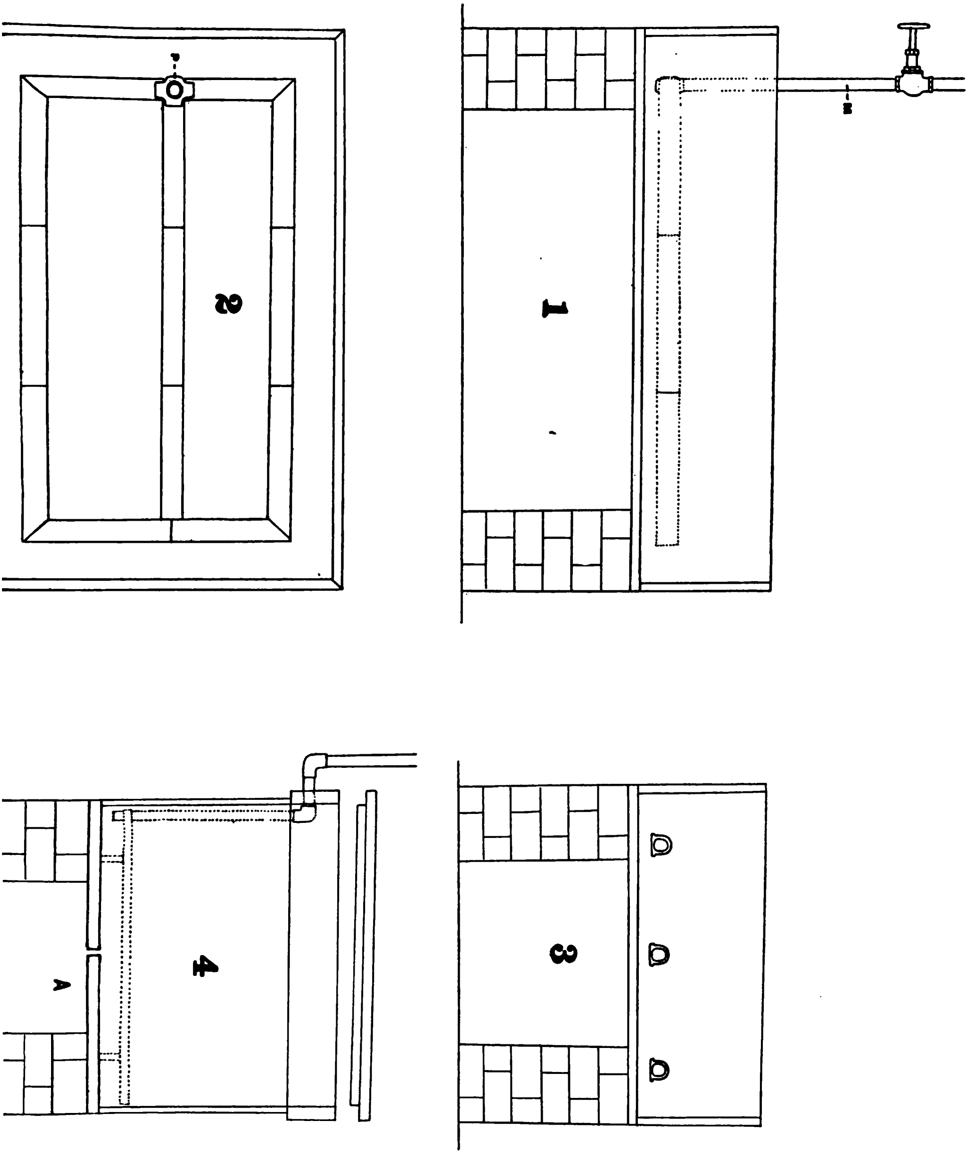
The results of these experiments are as follows:

Bed (a) was heated to 204° F. in 1.15 hrs.
Bed (b) “ “ “ “ “ “ 45 min.
Bed (c) “ “ “ “ “ “ 1.00 hr.
Bed (d) practically the same as (b).

These experiments show that bed (b) which was piped with three lengths of tile gave the best results, with bed (c) following, and the most unsatisfactory results were given by bed (a). Bed (d) gave practically the same relative results as (b). Bed (b) contained a few more feet of pipe than (c), and more than $\frac{1}{3}$ more than (a), and for this reason alone it might be expected that the heating of the soil in the bed (b) would be more effective. There is another more important difference, however, and that is in the method in which the steam circulated. The cross tiles in (c) were not nearly as effective as the middle lengths in (b), neither would they have been even if they had contained the same linear feet. Bed (a) would have heated more effectually if there had been a continuous loop. Had the four beds been piped the same and all connected at once with a large boiler maintaining a high pressure of steam they could have been heated in two hours time. The tile which were employed for sterilizing were left in the soil, but in these experiments they were not used for sub-irrigation purposes. Should the soil, however, be removed and replaced by other soil it would be desirable to remove the tile, which can, however, be easily put back. We have tried many different methods of piping with variations in the pressure of steam and we will state that in order to get the cheapest and best results it is necessary to pay attention to two points, namely, that the higher the pressure of steam maintained, the quicker and more effectual are the results, and the greater tile area in which the steam has to circulate the quicker it will find its way through the soil and accomplish the sterilization of the same. It is not only necessary that there should be a number of feet of pipe in the soil in order to sucessfully heat it, but the area of cross sections is equally important.

In regard to the cross section area of the pipe we will relate the results of one of our experiments in trying to sterilize a box of soil with $\frac{1}{2}$ in. lead pipe made up into a coil of four lengths. This coil had holes in it 2 in. apart and was placed in a box containing

16 cu. ft. of earth which was easily heated in one hour's time when three lengths of 2-in. tile were used and a pressure of 4 or 5 lbs. of steam. With the small lead pipe it was found that it was impossible to heat the soil after running it for a number of hours. The method just described is especially adapted to sterilizing soil in the bed where it is subsequently to be used in growing some greenhouse crop subject to nematodes. It should be stated, however, that certain beds are more suitable for this purpose than others. Soil can be more effectually heated in a narrow bed than in a wide one. Many of our cucumber growers raise their plants in a bed 15 or 18 in. wide, 8 to 12 in. deep, and 50 to 100 ft. or more in length. Beds approximating these dimentions could be easily heated in a short time at little expense, and in a cucumber house it would be most desirable to construct them after this manner. Not unfrequently, however, cucumber houses are not provided with benches but the vines are grown directly in the ground soil. In this case should sterilizing become necessary, the earth in which the plants are growing can be separated from the remaining soil by means of 12 in. boards or plank and this lot of earth can be tiled and then treated. The boards or plank arranged in this manner restrict the amount of soil to be treated and prevent contamination from the untreated. In case pots are used as frequently happens in tomato culture the earth can be sterilized in a special bed or the pots containing the earth can be placed in a tight box and sterilized, although this latter method is not so practical as pots take up more room than soil placed in a bed. For sterilizing small quantities of earth we make use of an ordinary small house boiler which heats our laboratory and seldom indicates more than 3 or 4 lbs. pressure of steam. This is connected with a box, (see fig. II., 1, 2, and 3), containing 15 cu. ft. of earth, in the bottom of which is buried three lengths of tile supplied with steam from the boiler. With a pressure of 3 or 4 lbs. of steam the box can be easily heated to 212° F. in one hour's time and this amount of earth will fill about fifty 10 in. pots. A small bed of this description would be exceedingly convenient for florists in sterilizing earth for such pot plants as cyclamens etc. Another convenient arrangement for sterilizing which we use for a variety of purposes is shown in fig. II., 4, which represents a cross section of a box, but it is not adapted for sterilizing earth except when in trays or pots. This is simply an ordinary zinc lined box. It is provided



g. II Showing the details of a small sterilizing apparatus. 1, 2, and 3 represent various ions of a box furnished with tile and capable of holding 15 cu. ft. of earth. (m) steam pipe from er. (p) four way connection which enters the tile. 4 represents a cross section of a zinc lined and cover for sterilizing pots and small boxes of soil. (a) valve or hole for drawing off the ensed steam.

with a wooden cover of double thickness which with the use of an old blanket makes it fairly tight. The steam pipe enters in one side near the top and passes down the inside to within an inch of the bottom. A wooden support made up of slats keeps the object to be sterilized from touching the bottom, and a valve (a), or much simpler, a hole plugged with a cork, allows for the drawing off of the condensed steam which gathers in the bottom of the box. This manner of sterilizing[1] is very convenient for steaming small boxes of earth, pots, etc., as it can be done in a very short time, and at very little expense. An old zinc lined refrigerator, however, could be substituted for the box to good advantage. The method of ridding the soil of nematodes where such plants as cucumbers, tomatoes, etc., are sown and where the crop is obtained from the seed offers fewer obstacles than such plants as violets where transplanting is accomplished by separation, as the latter process necessarily includes taking some of the old soil with the plant. If the violet plants are affected with nematodes it must be clear that the separating and transplanting of the plant into new soil would infest it whether sterilized or not, and result in a crop of sickly plants covered with leaf spots and few flowers. The only method which can be employed at present to control this trouble would be to start cuttings of the violet in sterilized earth, and when the cuttings were ready to transplant to place them either out of doors in some newly turned up land, or land which had not been contaminated with nematode infected manure, or else into earth in the greenhouses which has previously been sterilized. Experiments with violets are now under way and we shall report them at some other time. The manner in which roses are propagated also gives rise to similar obstacles in regard to nematode infection. If the same care is taken in regard to contamination as in violets the nematode problem is one which need give no alarm. Some rose growers in Massachusetts have never been troubled with nematodes. Mr. Montgomery who possesses considerable skill, knowledge, and experience in rose growing and who has charge of the extensive Waban conservatory at Natick, informs us that they have never been troubled with nematodes upon their roses. They make a practice of using soil composted with cow manure which is allowed to remain out over winter. There is no doubt that owing to this method of preparing the soil they are able to keep nematodes in check.

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[1] Since the above was written Prof. Britton has described a similar box in the Annual Report of the Conn. Expt. Station p. 310, 1897. He uses wooden trays which just fit the box, the bottoms of which are covered with galvanized iron netting which makes it more desirable for sterilizing earth.

Cost of Sterilization.

The expense of sterilizing the soil will largely depend upon one's equipment and the conditions under which it has to be done. If one has a large steam boiler which he uses for heating his houses, then the necessary expenses involved would not be very great. The expense of purchasing tile, or steam pipe if one happens to use such, which in the latter instance would have to be drilled and connected, would be the heaviest to bear. We prefer tile to steam pipe and think they are fully as effective, and then again they can be used for subirrigation purposes, a practice which according to those who have experimented with it gives beneficial results. On the other hand if one had to purchase a steam boiler together with the tile the first expense might be of some account. The 2 in. tile, however, cost about one cent each, or purchased in quantities somewhat less, and are slightly over one foot in length, and a second hand steam boiler* of 6 or 8 horse power giving a pressure of steam equal to 40 or 80 lbs. can be purchased for about $50 or $60, and would answer the purpose for most greenhouse growers. Larger boilers would be better as they carry more water, a necessary feature in this kind of work, inasmuch as there is considerable water used up in heating owing to the condensation of the steam. The soil in a bench 12 in. deep, 15 in. wide, and 80 ft. long, or in other words 100 cu. ft. of soil, in which were placed two lengths of tile 2 or 3 in. from the bottom, could be easily heated in one and one-half to two hours time. The tile in such a bed we will say costs $1.75 and the extra expense for coal would be unimportant. Some further idea of the expense of heating the soil can be obtained from the amount of soil employed and the time required to heat it to 212° F. as ascertained by Galloway and others. According to Galloway he succeeded in heating about 72 cu. ft. of earth in two hours time. Lodder's beds evidently contained 480 cu. ft. of soil which he heated in three hours, while Rudd's beds contained 600 cu. ft. which he

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***In purchasing a second-hand boiler of high pressure it would be well to obtain the State Inspector's certificate.**

heated in two hours, and according to Mr. May he heats 112 cu. ft. in one and one-half hours.

Effects of Heating the Soil on the Growth of the Crop.

In the numerous crops of cucumbers, tomatoes, and lettuce which we have grown in sterilized earth we have never noticed any thing of a detrimental nature, but on the other hand a decidedly beneficial effect as the result of sterilization. Not only is this shown in the difference in color which the plants take on, but in an appreciable acceleration of their growth. We have repeatedly run parallel cultures of sterilized and unsterilized soil and have invariably noticed these effects on cucumbers and lettuce. Mr. W. N. Rudd whom we have already quoted as having tried the sterilizing method says as follows[1]:—"One would imagine that the cooking would make the soil soggy, but it has no such effect, and indeed the soil seems in better condition afterwards than before the steam was applied, and the fine condition of the plants growing in soil which has been treated proves that the soil has not been injured in the least." It has long been known among practical gardeners that heating the soil produces beneficial results. Every greenhouse soil contains humus or vegetable mold and it is recognized by vegetable physiologists that the presence of humus in the soil plays an important part in assimilation and plant growth, but its efficiency depends partly upon the stage of decomposition at which it has arrived. It has been shown by experiments in which plants are treated in one case with humus in the raw condition, and in the other with humus which had been subjected to the action of steam for several hours at a temperature of 212° F., that there is considerable difference in the yield of the crop. It has been found that the same quantity of soil, after the action of heat, yields a crop many times in excess of the former or untreated soil. In other words by heating we convert the humus compounds in the soil into a more available form for the utilization of the plant. That the heating of the soil gives rise to some changes is shown by its darker color and more porous condition, and it is undoubtedly due to these changes which have taken place in the humus compounds which account for the accelerated and vigorous growth of the plants. Another feature which is characteristic of sterilized soils is the unusual occurrence of humus loving plants, or saprophytes, that grow upon it, which is a good indication that the organic matter contained in the soil has undergone changes through the action of the heat. We have ourselves observed more than once certain species of saprophytic fungi growing upon our steamed beds which have never shown any tendency to grow on unheated soil, although with the exception of being steamed the soil was exactly the same as that upon which they never appeared.

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[1] American Florist, Vol. IX, p. 171-197.

Effects of Heating the Soil Upon Other Greenhouse Pests.

Besides the destruction of nematode worms, and the gaining of robust and vigorous plants which steaming the soil gives rise to, there are other beneficial effects worthy of being taken into consideration. Many of the fungous and insect pests to which our greenhouse plants are subject find their normal habitat in the soil. In our experiments upon heating the soil in the beds we killed thousands of red spiders, and we presume that we did the same with the cucumber aphis, or with the eggs, as we were remarkably free from them, although the soil had previously been used for cucumber crops which were badly contaminated with aphis. This latter statement, however, in regard to killing the aphis, is nothing more than a conjecture, as Entomologists tell us that they do not know where the aphis breeds, but they surmise that it breeds upon particles of organic matter in the soil or upon the old cucumber vines thrown out upon the compost heap. The soil undoubtedly harbors many of the spores of the mildews which are common to cucumbers, tomatoes and lettuce.

One of the most common and troublesome diseases to young cucumbers is the so-called "damping fungus," Pythium De Baryanum, which attacks the young plants at the surface of the ground and causes them to wilt and collapse. We have repeatedly found as a result of heating that this did not make its appearance when they were subjected to a temperature which was over 140° or 150° F.; when, however, the temperature went below these points the fungus appeared to be accelerated in its growth and development and damping was more likely to show itself than in normal pots. This fungus must be distinguished from the ordinary "damping fungus" (Botrytis) which attacks begonia cuttings, etc., in the propagating pit. Sterilizing the soil for this fungus would be of no account as the spores (conidia) of this species are everywhere and only await a favorable opportunity to germinate and develop themselves, whereas with the Pythium the conditions of dissemination are much more restricted. What is true in regard to the Botrytis is probably true in regard to some of the mildews, as there is no reason to doubt that the spores can thrive in the house for some time without coming in contact with the host, although sterilizing the soil would undoubtedly kill many of them. The so-called "drop" in the lettuce which is caused by a facultative parasite, a species of Botrytis, is also completely controlled by sterilization. This fungus causes no end of trouble to some lettuce growers and is confined entirely to the soil where it propagates only by means of its mycelium, but it frequently becomes disseminated from one part of the house to the other by means of the gardener's tools. Sterilizing the soil has also an effect upon the weed and grass seeds which constitute more or less of a nuisance in a house. The difference between a heated bed and one that is not heated is very marked indeed in this respect. In the beds which were heated at 204° F. there were no weeds or grass seeds to trouble us and the only things appearing were one or two clover plants. The seeds of the clover appear to be more resistant than other seeds and their presence can be accounted for probably by the fact that the temperature at certain points did not quite reach 204° F. In the beds that were not heated we hoed under a number of crops of weeds as the horse manure which was mixed with our soil was largely contaminated with seeds.

Relation of Nematodes to their Environment.

A knowledge of the relationship of the environment to an organism is of considerable importance in all experiment work where we have to deal with some pest which causes injury to our economic plants. Indeed some of the methods of controlling nematodes are based upon a knowledge of the influence of the common external factors or agencies which go to make up the environment and to which all organisms strive to adapt themselves. Such for example is the desiccation method which forms an important factor in the treatment recommended by Vanha.

The external factors playing an important part in the life history of an organism are heat, light, moisture, etc., and it is the variation of these ever changing factors with which the organism has to contend, and which gives rise to characteristic manifestations in its activities.

Every organism, however, is limited in its power to withstand the effects of these external forces. The range of susceptibility is represented by what is known as a minimum, optimum, and maximum condition. Whenever this range is disregarded, or in other words whenever the minimum or maximum conditions of the organism are passed, death results, but what constitutes the minimum, optimum, or maximum condition for one organism does not necessarily constitute the same for another and hence arise specific forms of susceptibility or powers of response in organisms.

EFFECTS OF HEAT.

We have already shown the effects of heat upon nematodes. A temperature of about 140° F. kills them and destroy the eggs, but they appear to thrive at those temperatures of the greenhouse soil which may vary anywhere from 45° F. to 75° F. The optimum temperature for Heterodera is probably not far from 60° to 70° F.

EFFECTS OF COLD.

Undoubtedly most, if not all, of the non parasitic forms of nematodes found here are indigenous to our northern climate, as their eggs will stand our severest winter temperatures. The adult worms, however, are easily killed by freezing as we have frequently seen in our experiments. That the eggs of these species can stand low temperatures is shown by an observation on old squashes which we have examined after they had lain upon the ground most of the winter and been subjected to alternate thawing and freezing even at a temperature equal to 20° F. below zero. When the squashes were brought into the laboratory no nematodes could be found, but when moistened with sterilized water and examined again after having remained in a warm room a week or ten days they were swarming with nematodes. We have observed the same thing in cultures of nematodes which we purposely allowed to freeze. This, however, does not apply to the parasitic species such as Heterodera which attacks cucumbers, tomatoes, violets, etc., inasmuch as this species is not native and freezing always kills the adult worms and their eggs. We have repeatedly shown this to be the case by allowing badly infested nematode soil to become frozen and on making thorough examinations of the soil afterwards have never found nematodes.

EFFECTS OF MOISTURE AND LIGHT.

A certain degree of moisture is evidently essential to nematodes and they do not appear to suffer much from an excess of it, as we have kept them in watery solutions for days at a time with no detrimental results. While nematodes naturally prefer the dark, as does their relative the earth worm, their exposure to light, as far as we have observed, causes no appreciable harm and they appear to multiply and thrive as well in it as they do in darkness.

EFFECTS OF ELECTRICITY.

Some experiments were made with nematode infested earth with alternating electric currents of varying strengths. The infested earth was placed in a glass tube $\frac{3}{4}$ in. in diameter and the various samples were subjected to different strengths of an alternating current for a period of one minute each. It is sufficient to say that the experiments proved of very little value, but they indicated that the amount of current necessary to rid the soil of nematodes would have to be large enough to produce considerable heat in the soil and at the present time there is no indication that this method of treatment would be practicable. We have demonstrated by experiments in our laboratory that the amount of alternating current which seeds can stand without being destroyed is largely determined by the amount of heat they are capable of enduring and in all probability the same would hold true of nematodes. There is reason to believe, however, that this statement would not hold good for direct currents. A current sufficiently strong to produce electrolysis in an organism would probably cause disintegration and death to nematodes.

EFFECTS OF DESICCATION.

Neither nematodes nor their eggs can stand desiccation. Jars containing innumerable nematodes were allowed to dry at the temperature of the laboratory and when examined one year afterwards, after having previously been moistened with sterilized water for some weeks, showed no evidence of nematodes. The same results have been obtained when we allowed nematode infested earth and other infested material to become dry. It is hoped that some practical use can be made of this fact in treating nematodes in greenhouses.

NATURE OF THE SOIL AS EFFECTING NEMATODES.

Some observers[1] have maintained that when artificial soils such as coal ashes mixed with peat were used, nematode galls were not formed except in the small ball of earth clinging to the plants when transplanted. It might be supposed that a soil of the nature of coal ashes would not constitute a favorable medium for nematodes and we have never observed any galls on plants in this medium, although we have obtained them abundantly on roots cultivated in peat soil and also to a certain extent in sawdust cultures. A single experiment made with a 10 in. pot of peat containing cucumbers will suffice to show that nematodes will thrive in a strong acid soil such as peat. About a thimblefull of nematode infested earth was inserted 1 in. beneath the soil close to the plant. Six weeks later the plant was taken up and examined and there were more than one hundred galls upon the roots. Cucumbers were again planted in the pot and their roots likewise became covered with galls. Nematodes in all probability can thrive to a limited extent in every soil in which their host plant is capable of flourishing, although there are certain soils such as coal ashes which do not appear to be especially adapted to their development and growth.

INFLUENCE OF CARBON-DIOXID AND OXYGEN.

All animals require Oxygen although not in the same degree. The fact that nematodes live in the soil which is richer in Carbon-dioxid than the air would indicate that they are normally adapted to a larger percentage of this gas than ordinary animals, and since they thrive in decomposing manure heaps they must be subject to a great variety of gases and chemical solutions of a strong nature. We observed, however, that when nematodes were placed in an atmosphere containing 85% of Carbon-dioxid their movements largely ceased in a very few minutes, but as soon as air was supplied, they resumed their movements.

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[1] See experiments of E. H. Jenkins and W. E. Britton in Conn. Agrl. Expt. Station Report, 1895, p. 92.

Resumé.

Nematodes are small, mostly microscopic worms allied to the earth worm; many are entirely harmless, some are parasitic in animals, and a few in plants. Of the many species occurring in this section only one is known to damage plants. This is called Heterodera radicola and is the cause of the so-called "root-knot" disease of many plants. The species is very similar to and perhaps identical with the European H. Schachtii which causes so much damage to the sugar beet.

The amount of damage caused by nematodes to economic plants throughout the world is quite large.

The number of families and species of plants subject to nematodes are numerous. They not only attack the roots but frequently other parts of plants as well.

Certain species of nematodes, Tylenchus, etc., are indigenous to our climate and by means of their resistant eggs they are capable of surviving our winters, but the parasitic species Heterodera cannot.

The greatest amount of injury done to plants in the Northern U. S. is largely confined to greenhouses and occurs to such plants as the cucumber, tomato, violet, rose, cyclamen, etc. which are affected in their roots. Not infrequently, however, outdoor plants are subject to nematodes by being brought in contact with infested earth or manure.

Plants affected by Heterodera usually appear sickly and gradually fade away and die. The roots of such plants are found to be more or less covered with various sized galls or swellings. These galls are the result of an abnormal growth of the root due to the young worms forcing their way into it, and there remaining to complete their development. The damage to the plant is not due to the feeding of the worms upon the roots, but rather to the fact that the flow of sap from the root is cut off by the abnormal development of the tissues.

The nature of the problem of nematode control is one which must be based upon a knowledge of the life history and environmental conditions affecting the organism.

It has been found that the use of chemicals is of no practical value. None of the chemicals which we have used are capable of killing the eggs of nematodes when confined in the soil, and unless this is accomplished the treatment is of no account.

There are many solutions capable of killing a certain percentage of adult worms and that can be applied to the soil before or after planting, but the strength and the amount of the solution necessary to kill nematodes in the soil is considerably greater than that necessary when the worms are isolated. This is due to the difficulty of bringing the solution into contact with each particle of matter in and around which the nematode thrives.

The most effectual, complete, and practical method at the present time of exterminating nematodes in greenhouses is by heating the soil by means of steam. This can be accomplished without much expense providing proper attention is paid to the methods of applying the steam.

A pressure of steam exceeding 50 lbs. is not only cheaper, but more effective than a pressure which falls below this, and the amount and cross section area of the tile is important. See p.53.

The cost of heating soil depends upon the equipment employed and cost of labor, etc. Probably not far from 100 cu. ft. of soil under the most favorable conditions can be heated in one hour's time to a temperature of over 200° F.

The minimum amount of heat necessary to kill nematodes and their eggs while confined to the soil is about 140° F., but for all practical purposes it is desirable to make use of a higher temperature, at least from 180°-212° F.

The benefit of steaming or sterilizing the soil is not alone confined to the destruction of nematodes. Many other greenhouse pests are killed. The mechanical conditions of the soil are moreover greatly improved; the humus compounds are rendered more available for plant food, which results in giving plants grown in sterilized soil a considerable acceleration in their rate of growth.

The changes of the environment which appear to affect Heterodera the most are freezing and desiccation. Either of these agencies might be employed in certain cases to kill nematodes. The latter gives promise of becoming a cheap and efficient method.

Explanation of Plates.

Plates I. and II. Development of a free.living nematode, Rhabditis sp. Pl. I. Figs. 1-12, development of embryo in the egg. × 350. Fig. 13, young worm just hatched; m, mouth; o, oesophagus; x & b, oesophagal bulbs; s, stomach or intestine; r, rectum; a, anus; p, location of sexual organ, shown more enlarged in fig. 14. Figs. 15, 16, 17, further development of the female, showing ovary at o, and vulva at v, fig. 17. Fig. 18, male and female in copulation. Figs. 13, 15, 16, 17, 18, × 135. Plate II. Figs. 1-4, further development and maturity of female. Fig. 3, mature female; l, lips; o, oesophagus, with x and b bulbs; s, stomach; r, rectum; a, anus; v, vulva; e, eggs in various stages; w, young worms. Fig. 4, dead mature female filled with young. Fig. 5, mature male. Fig. 6, posterior end more enlarged; z, bursa; q, spicule; y, anus; u, spermatozoa. Figs. 1, 2, 3, 4, 5, × 135.

Plate III. Figs. 1-16, eggs of Heterodera radicola, showing development of the embryo. × 325.

Plate IV. Development of the female Heterodera. Fig. 1, young worm just hatched. Figs. 2, 3, and 4, stages of development in the swelling up process of the female. Fig. 5, stage at which copulation takes place; h, spear; k, bulb; g, vulva; e, anus; c, ovary; w, stomach or intestine; d, rectum. Fig. 6, mature female with ovary tubes partly visible. All × 100. Fig. 7, ovary, more enlarged.

Plate V. Development of male Heterodera. Fig. 1, just hatched, indistinguishable from the female. Fig. 2, beginning of male metamorphosis, showing the body drawing in from the wall, and at t, the rudimentary testis. Fig. 3, same in later stage. Fig. 4. mature male, about to emerge from old body covering. Fig. 5, mature male; c, cap-like thickening on head; s, spear; e, excretory canal; t, testis; x, spermatozoa; i, intestine. Figs. 1, 2, 3, × 175. Fig. 4, x 90. Fig. 5, × 500.

Plate VI. Sections of normal and nematode-attacked cucumber roots, at various ages. Fig. 1, very young, normal root. Fig. 2, mature, normal root; c, cortex; p, central cylinder; d, ducts. Fig. 3, young root same age as fig. 1, attacked by nematodes. Fig. 4, same, one week later. Fig. 5, section of mature gall, showing distortion of tissues. All × 20.

Plate VII. Fig. 1, tip of cucumber root with young nematodes just entering, enlarged. Figs. 2, 3, and 4, seedlings of rape, cucumber, and tomato, from badly infested soil. Fig. 5, young Heterodera among the particles of a fine loam soil, × 175. Fig. 6, portion of an angle worm contrasted in size with Heterodera, represented by the two black lines near the center,the longer representing the length of the mature male, the shorter that of the young worm. × 10.

Plate VIII. Species of free living nematode.

Plate IX. Various forms of nematodes; figs. 1, 3, 4, 8, 5, free living species.

Plate X. Photograph showing the effect of nematodes on cucumbers grown in pots. The plants in the two middle pots have died. The plants on each side are uninfected ones and of the same age as the infected plants.

Plate XI. Cucumber root showing galls.

Plate XII. Tomato root showing galls.

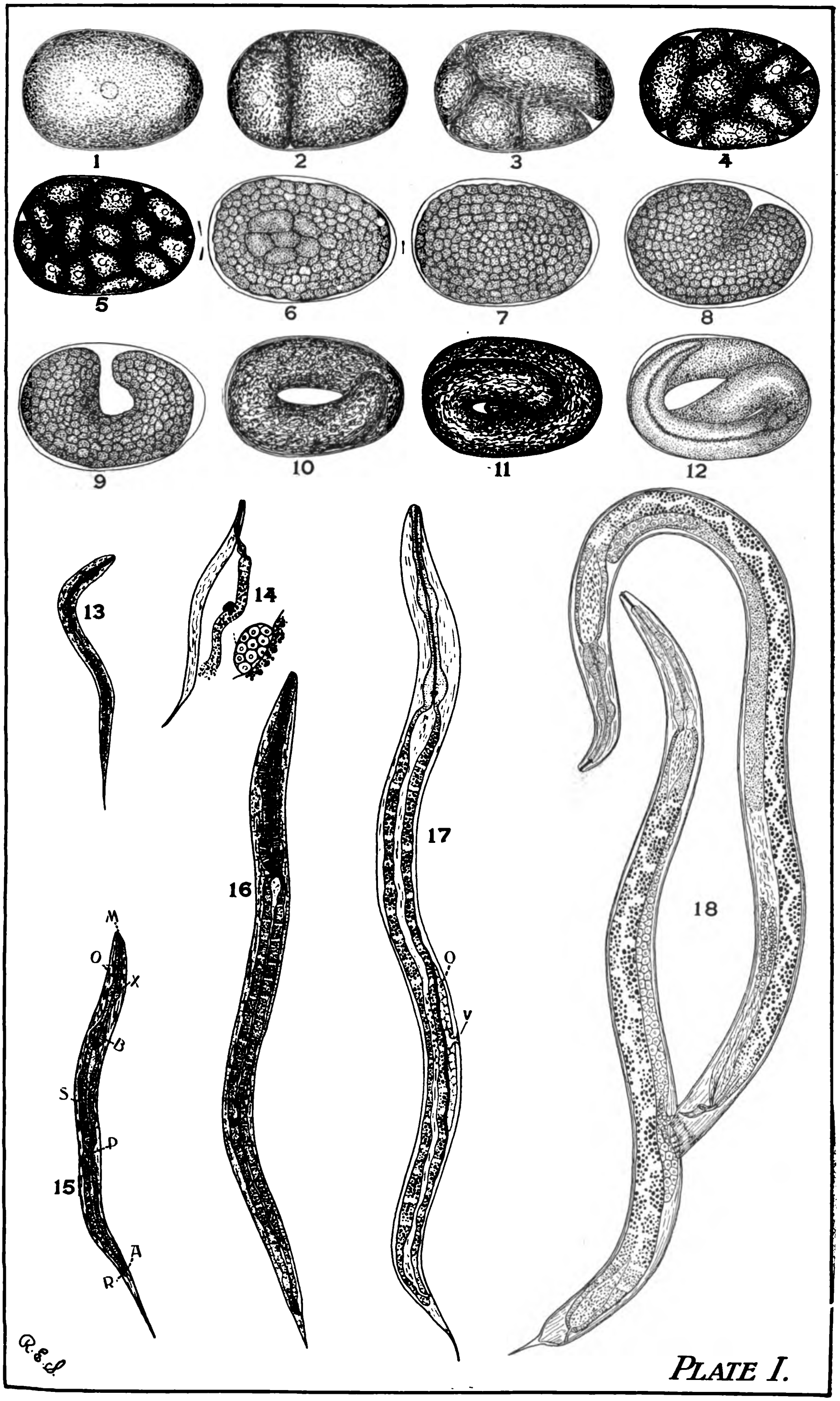
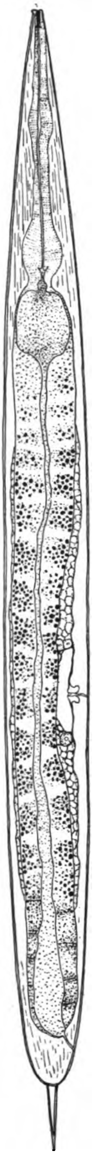


PLATE I.

PLATE II.



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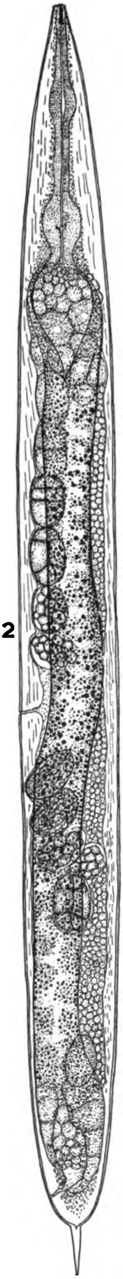

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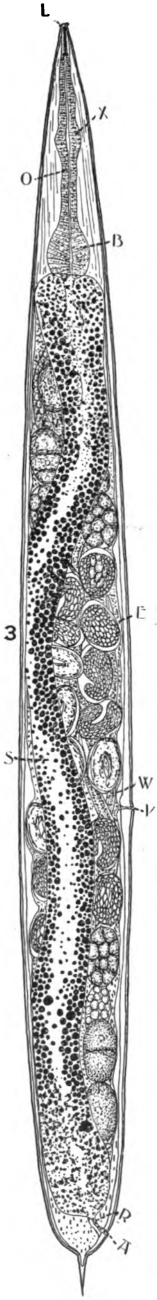

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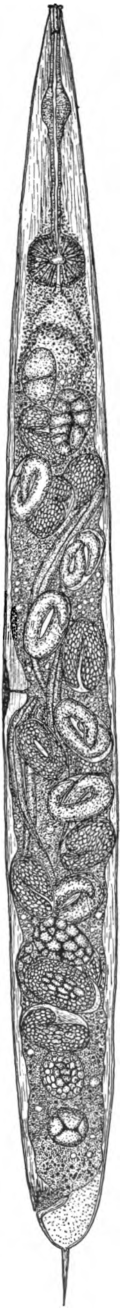

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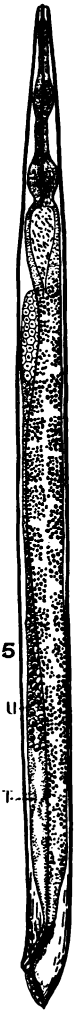

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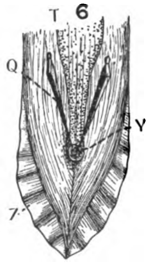

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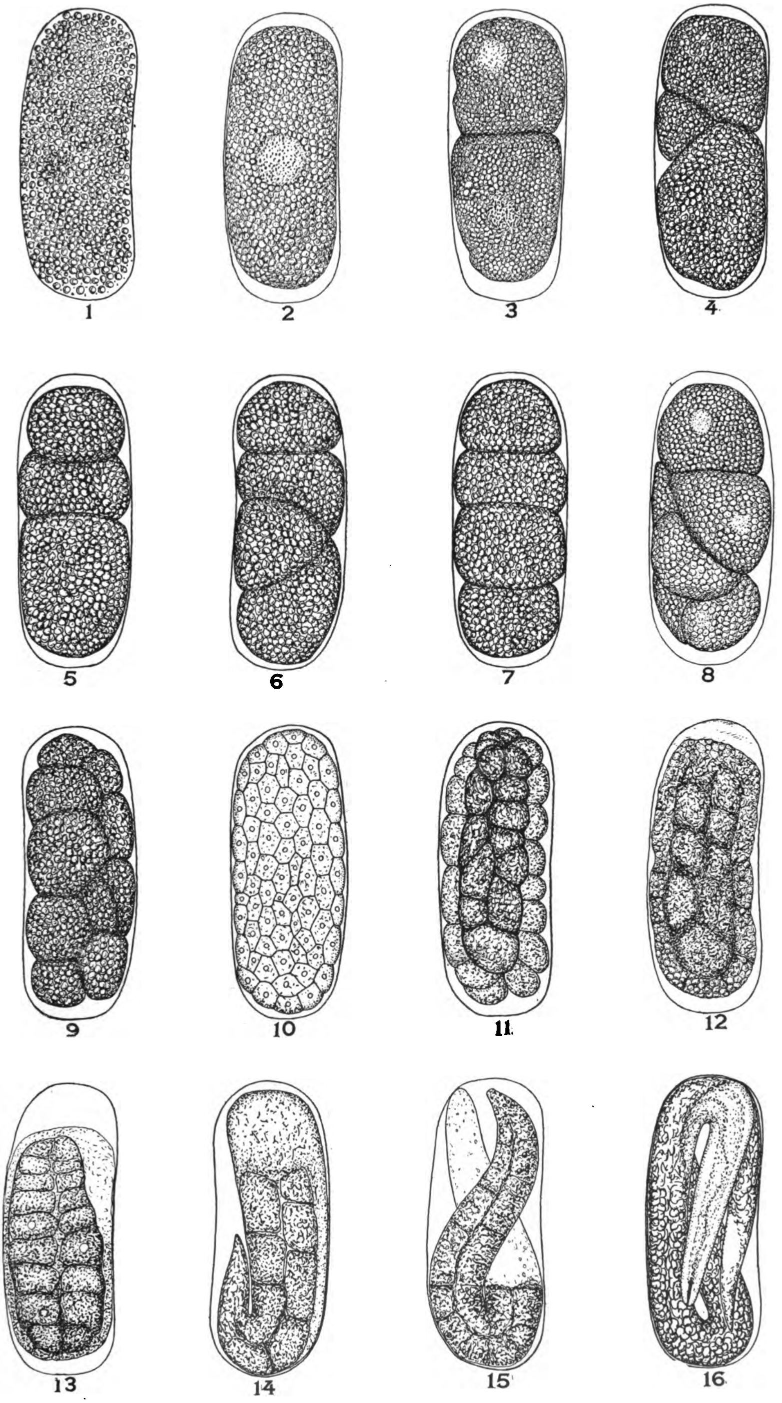
PLATE III.



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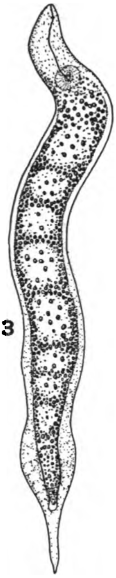
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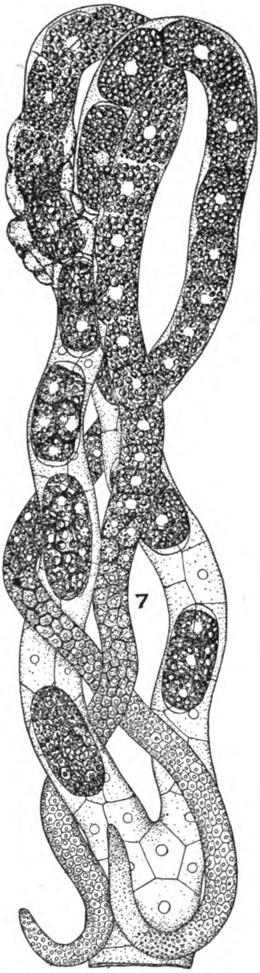
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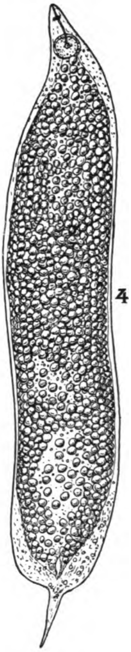
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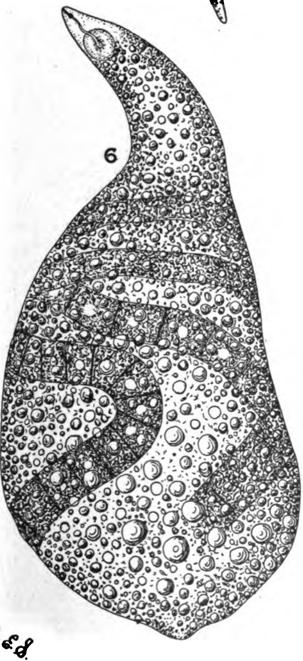
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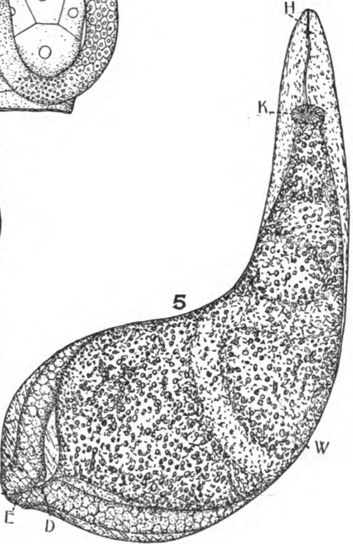
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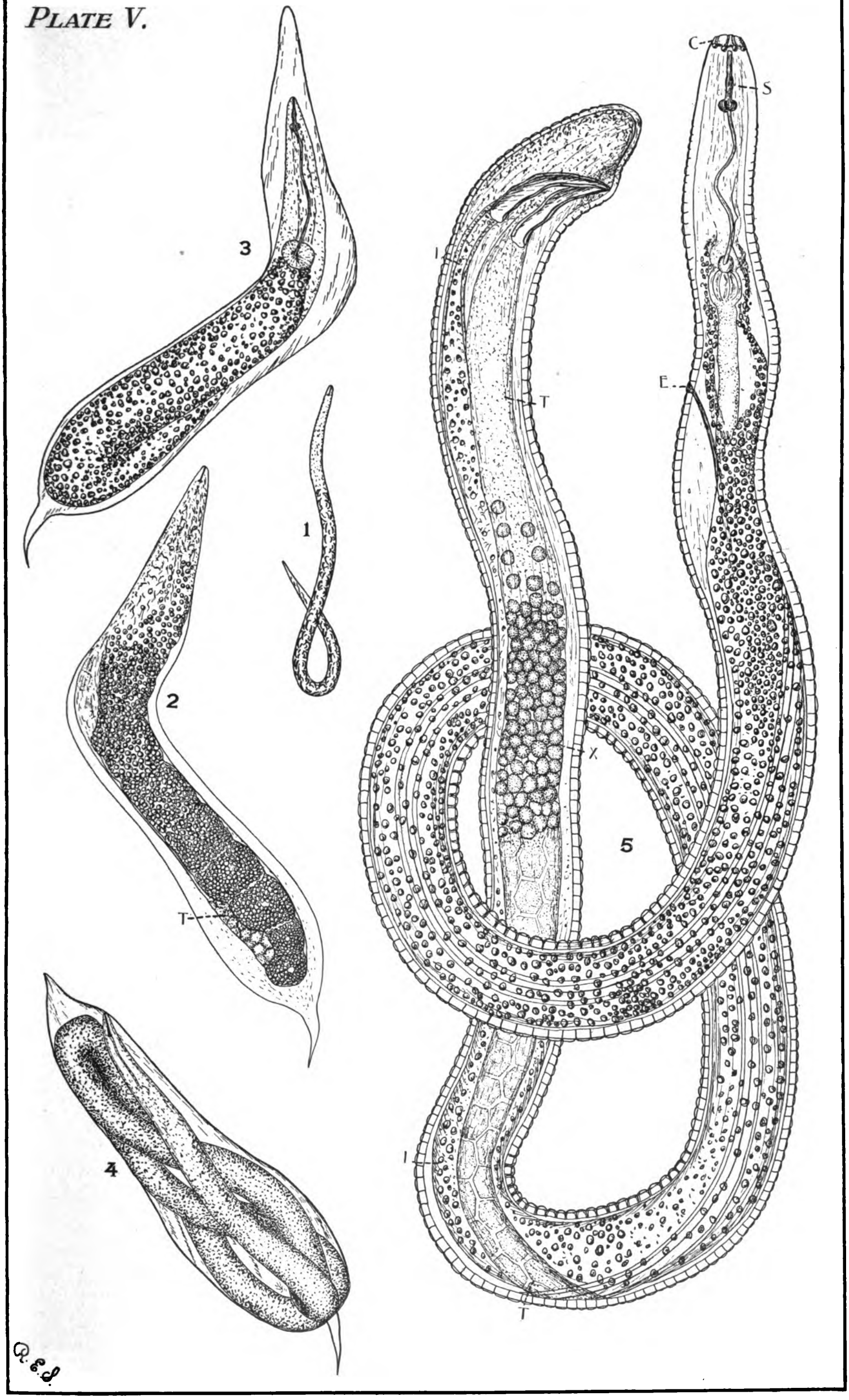
PLATE V.



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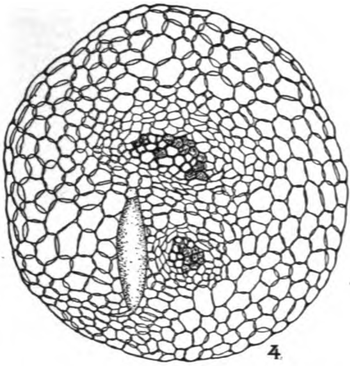

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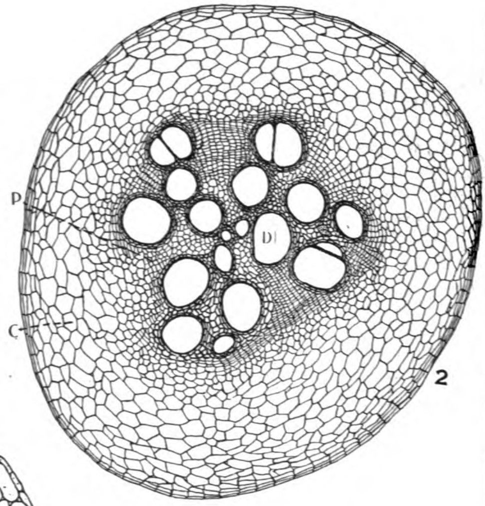

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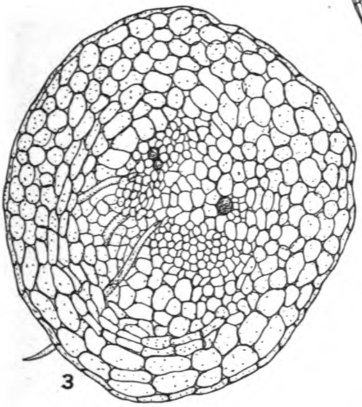

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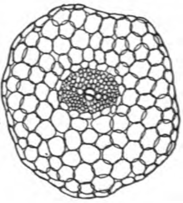

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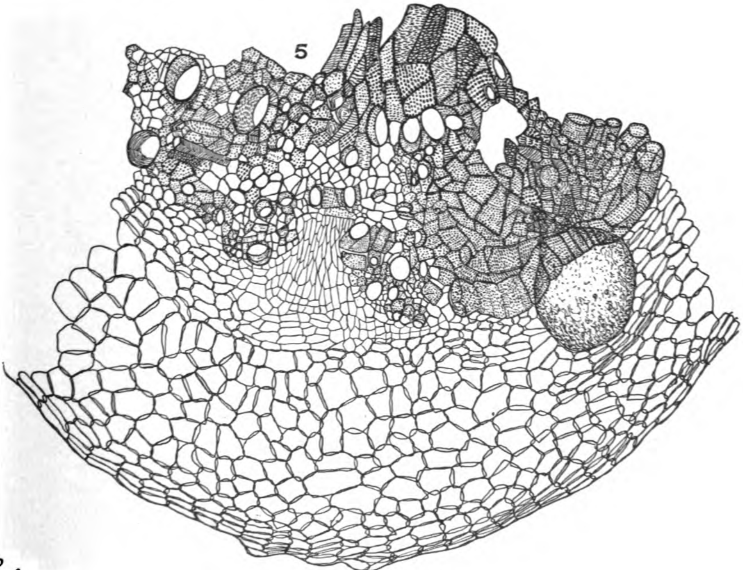

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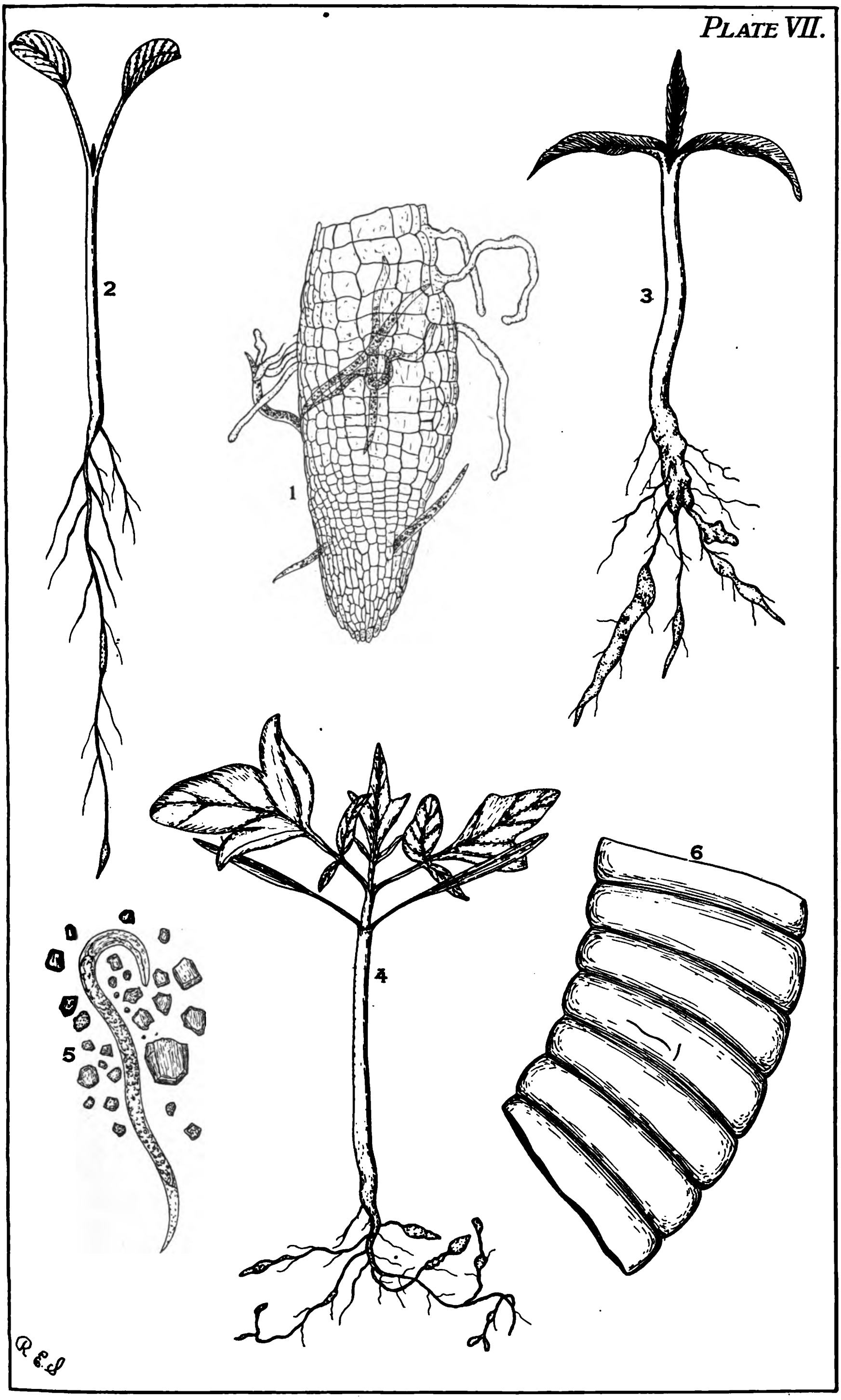

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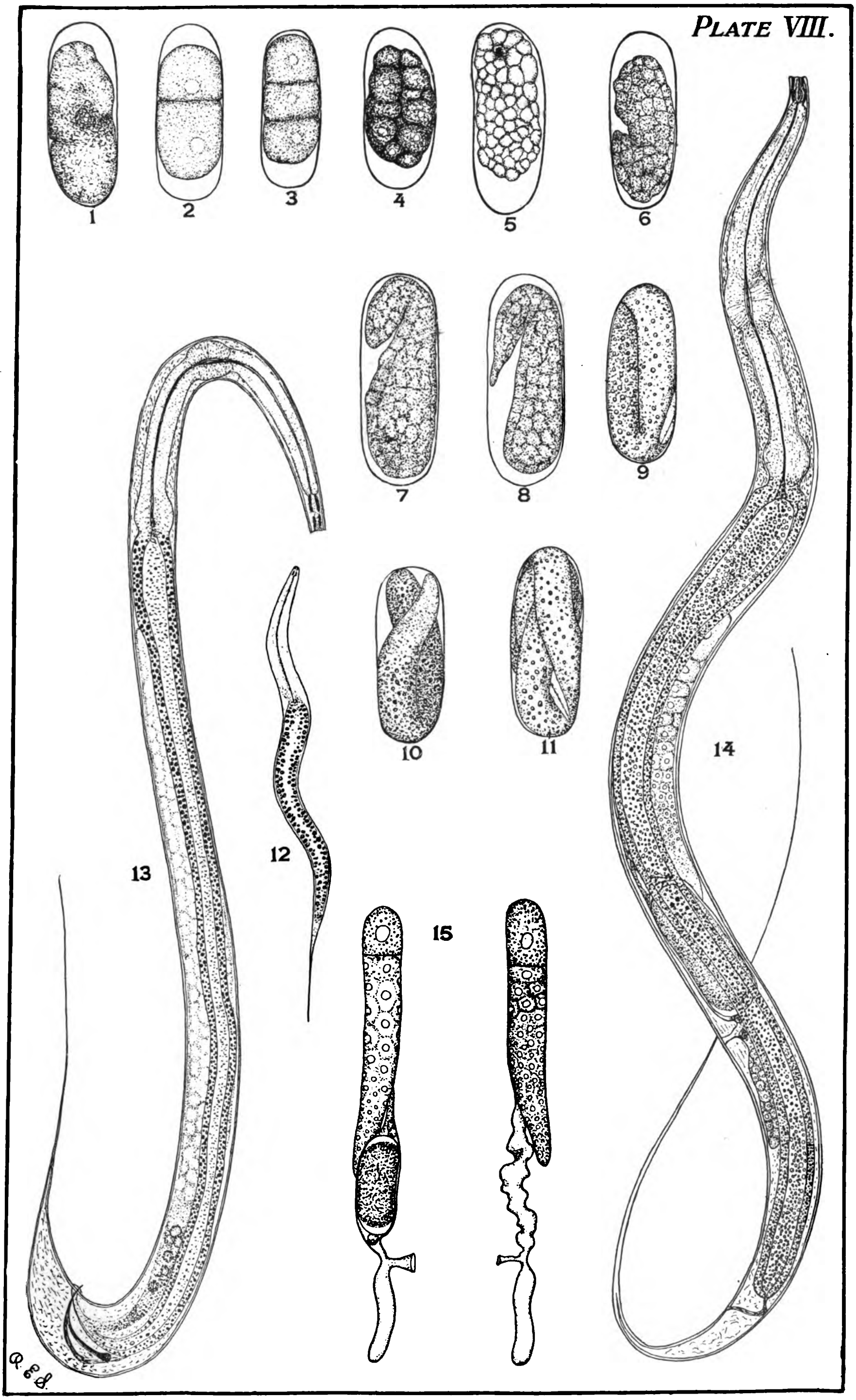

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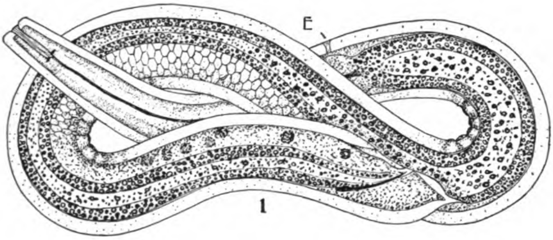

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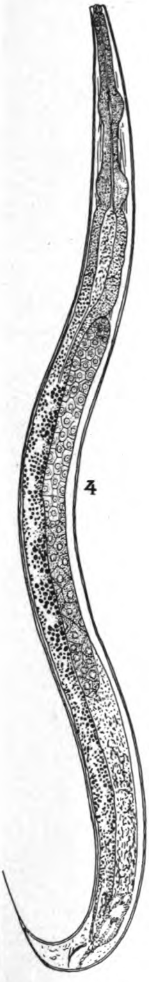

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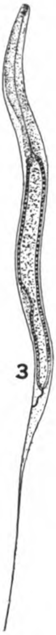

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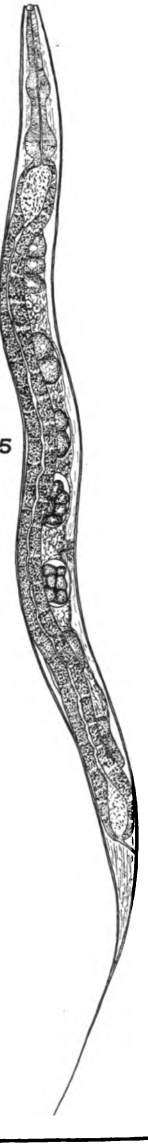

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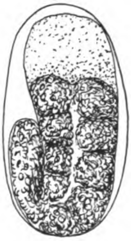

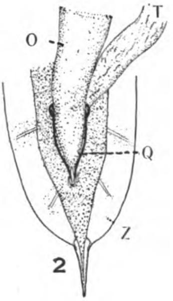

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PLATE X.

PLATE XI.

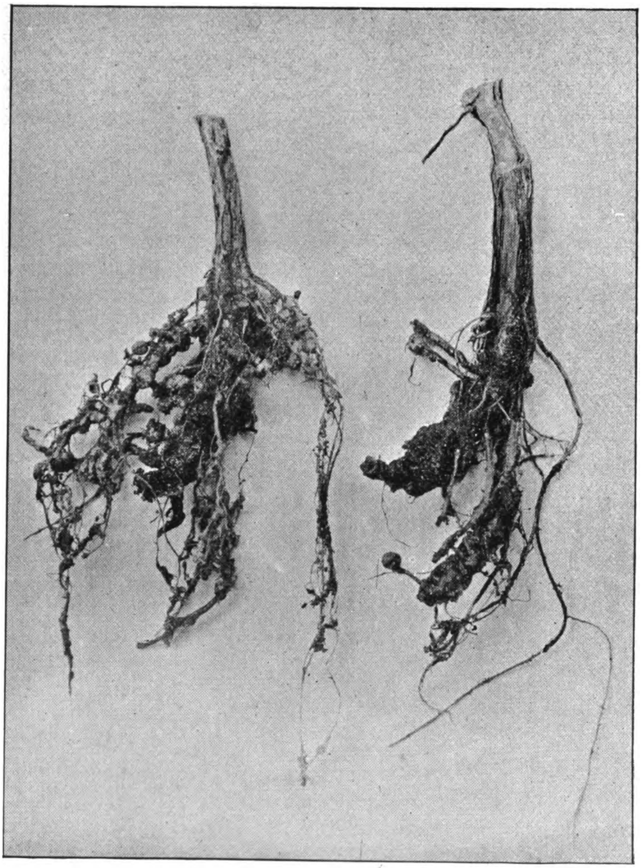

PLATE XII.